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ADVANCED FUEL SYSTEMS FOR RAMJET-POWERED VEHICLES

MATERIAL SELECTION FOR FUEL SYSTEM SIMULATOR

Donald H. Sargent and Cedric Bielawski

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Alexandria, Virginia 22314

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TECHNICAL REPORT

Air Force Aero Propulsion Laboratory
Air Force Systems Command
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FOREWORD

This summary report was prepared by Atlantic Research Corporation, Alexandria, Virginia, under U.S. Air Force Contract F 33615-69-C-1849, Project No. 3012. The work was administered under the direction of the Aero Propulsion Laboratory, Mr. Jack Fultz, Project Engineer, APRA.

This report covers work performed from 30 June 1969 through 31 January 1970, in the program work packages concerned with materials compatibility. Other work packages of the program performed during this time period are not included in this report.

A previously published summary report ("Material Screening Report," TR-PL-9870-01, December 1969), documented the first 4 months of this effort and contained descriptive passages for the initial choice of materials and for the setup of the immersion, permeability, and stress corrosion tests. These descriptive passages are not included in this report, but much of the previously reported data are again included so that the basis for material selections is complete.

Dr. Kermit E. Woodcock was the program manager for Atlantic Research Corporation; Donald H. Sargent was the principal investigator; and Cedric Bielawski conducted the materials compatibility effort. Dwight E. Shelor, E. Paul Sullivan, Jr., and Courtland N. Robinson were responsible for special testing series.

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

The identification number assigned to this report by Atlantic Research Corporation is TR-PL-9870-03.

ABSTRACT

A 7-month compatibility effort was conducted on materials potentially useful in ramjet fuel systems using the dense hydrocarbon fuel RJ-5 (Shelldyne H). The results of this work were used to select materials for a full-scale fuel system simulator to be tested in the remainder of this program.

The candidate materials included eight metals and eight nonmetallic materials. Immersion tests were conducted on all materials at both room temperature and at 160°F, with the specimens evaluated by changes in appearance, volume, weight, tensile properties, and hardness.

Additional compatibility tests were conducted under a high shear environment typical of ramjet turbopumps and under vibrational and flexing loads typical of aircraft carriage and missile flight. For these tests, the materials were kept in contact with hot Shelldyne H.

Candidate bladder materials were subjected to hot pressurant gases from solid-propellant gas generators, while in contact with fuel in a simulated fuel cell. Low temperature mechanical properties were determined for these elastomers.

None of the eight metals (two steels, two stainless steels, two aluminums, and two titaniums) have shown any effect of contact with Shelldyne H. The fuel tank material selected was 4130 steel, from considerations of compatibility, ease of fabrication, and cost. Steels, stainless steels, and aluminums were selected for other components of the simulator.

The bladder material chosen was a Viton/Nomex composite, from considerations of fuel compatibility and hot pressurizing gas compatibility. It is expected that this material will be suitable for low temperature operation, but alternate materials and composites may be tested in the simulator. Viton was selected as the primary seal and O-ring material, with nitrile also to be tested. Nylon and Teflon, both compatible with Shelldyne H, will be used, where applicable, for components of the simulator.

Nitrile and silicone rubbers were shown to absorb a significant amount of fuel, swell, and lose tensile strength as a result of immersion. A nitrile/nylon composite material did absorb fuel and swell, but its tensile properties were not degraded. Ethylene propylene terpolymer was incompatible with Shelldyne H.

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INTRODUCTION

The overall objective of this program is to obtain reliable design data for the fuel systems of ramjet-powered vehicles. The fuel used in this effort is RJ-5 (Shelldyne H), a dense hydrocarbon liquid.

For purposes of this effort, the fuel system is defined as consisting of all components from the fuel tank to the fuel control inlet, i.e., fuel tank, bladders or other expulsion devices, insulation, valves, seals, transfer lines, pressurization subsystems, boost pumps, and possibly other specialized components.

Lifetime goals for the fuel system components are 2 years (minimum acceptable life) and 5 years (desired life) under the environmental conditions prescribed by MIL-STD-210A. During its lifetime, the fuel system may be subjected to the environmental stresses of ground storage and handling and of 100 or more subsonic aircraft carriage cycles. This fuel system must be capable of withstanding the environmental conditions of typical missile flight trajectories, while it is initiating and performing its fuel delivery function.

As part of the overall program, materials suitable for fuel system components, which would come into contact with RJ-5 and pressurant gases in a typical fuel system, were subjected to compatibility testing. The material evaluation effort was divided into three work packages. The first was a screening phase of 4 months' duration, completed 31 October 1969 and reported separately. The second phase consisted of more extensive testing for a 3-month period ending 31 January 1970 and led to a selection of materials for a fuel system simulator to be built and tested in this program. This report describes this second phase of the materials evaluation effort. The third phase is a long-duration (12-month) extension of the testing.

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SECTION II

TEST RESULTS FOR METALS

1. VISUAL OBSERVATION

Coupons of eight candidate metals (listed in Table I) were immersed in Shelldyne H, both at room temperature and at 160°F. In addition, control coupons of each of the metals were maintained at room temperature, not in contact with Shelldyne H.

With the exception of the 4130 steel, none of the metals under test changed in appearance. The 4130 steel in Shelldyne H at 70°F was slightly attacked by rust, but the control samples (in air) were also rusted as expected, to a somewhat greater extent than the immersed samples. This indication of corrosion inhibition by Shelldyne H is supported by the observation that no rust appeared on the 4130 steel coupons immersed in Shelldyne H at 160°F. To confirm that the rust is due to moisture and not to Shelldyne H, samples of 4130 steel were immersed in dried and degassed fuel in sealed vials at 70°F and at 160°F. These coupons have not shown any indication of rust, proving that steel and Shelldyne H are basically compatible.

In no case was the fuel discolored by any metal, either at ambient or at elevated temperature.

2. IMMERSION TEST RESULTS

Duplicate samples of each of the metals under each of the three storage conditions (control specimens at 70°F, immersed specimens at 70°F, and immersed specimens at 160°F) were tensile tested at regular intervals during the 7-month period. The tensile tests themselves were done at room temperature. The measured tensile strength, yield strength, and modulus for the individual specimens are tabulated in Appendix A, Tables A.1 through A.8. Table I lists the averaged test results.

It is apparent from the average values listed in Table I that there were no significant effects of Shelldyne H immersion upon the tensile strength, yield strength, or modulus of any of the eight metals. All differences between the average values for the various storage conditions were within the confidence band for random error sampling and measuring.

3. STRESS CORROSION

The U-bend stress-corrosion specimens of each of the eight metals were under test for 158 days, with no evidence of failure. The 4130 steel specimen was lightly rusted above and below the Shelldyne H liquid level.

Table I. Average Immersion Test Results, Metals.

Metal	Storage Temperature (°F)	Tensile Strength (psi x 10^{-3})	0.2 Percent Yield Strength (psi x 10^{-3})	Modulus (psi x 10^{-6})
4130 Steel	70[a]	70.1	43.7	26.9
	70	70.7	41.2	27.6
	160	70.5	42.4	28.0
4130 Steel (cadmium plated)	70[a]	68.9	41.2	30.9
	70	64.8	41.7	30.1
	160	65.3	40.4	33.0
321 Stainless Steel	70[a]	82.8	30.0	25.3
	70	81.9	27.9	23.5
	160	79.5	28.7	25.9
14-8 Stainless Steel	70[a]	127.2	53.3	34.8
	70	131.7	54.3	39.6
	160	132.1	54.3	34.9
7075 Aluminum	70[a]	76.7	60.1	17.7
	70	79.6	66.0	22.1
	160	77.0	62.7	14.0
6061 Aluminum	70[a]	45.0	38.5	17.3
	70	42.9	38.8	18.2
	160	41.7	39.7	17.6
Titanium (6 aluminum-4V)	70[a]	168.4	157.2	32.9
	70	165.9	153.7	33.9
	160	165.1	146.7	33.7
Titanium (5 aluminum-2.5 tin)	70[a]	137.9	123.6	30.3
	70	137.9	116.1	28.2
	160	139.9	113.2	28.1

[a]Control samples not immersed in Shelldyne H.

SECTION III

TEST RESULTS FOR NONMETALS

1. VISUAL OBSERVATION

The eight nonmetals listed in Table II were immersed in Shelldyne H at 70 and 160°F. In addition, control samples not immersed in Shelldyne H were maintained at both temperatures.

Visual observation of the immersed specimens revealed that the ethylene propylene terpolymer (EPT) became heavily swollen. Moderate swelling was evident with nitrile rubber and with silicone rubber. No apparent change in the specimens was evident with the other materials.

The fuel, at room temperature and at 160°F, was heavily discolored to orange-yellow by the EPT and lightly discolored by the nitrile, the nitrile/nylon, the Viton, and the Viton/Nomex. The fuel with the nitriles appeared more discolored than the fuel with the Vitons, and the nitrile and the Viton with nylon reinforcement discolored the fuel less than the same rubbers without nylon reinforcement.

To quantitate the appearance of the fuel, the transmission of light (of known wavelength) was measured, using distilled water as a standard. Figure 1 shows the severity of the light absorbency and documents the color ranking discussed above.

2. IMMERSION TEST MEASUREMENTS

At various intervals in time, the progress of the immersion tests was documented in several ways. First, the appearance of the coupons and the fuel were noted. Second, duplicate coupons of each material at each storage condition were tensile tested. For the nonmetals, dimensional and weight changes were measured for duplicate coupons (especially designated for this purpose) of each material at each storage condition. Shore A-2 hardness was also measured in four places for each of two coupons at each storage condition.

Appendix B lists the data for individual specimens of the nonmetallic materials in Tables B.1 through B.8. The averaged results for the immersion tests are listed in Table II. These results will be discussed separately for each material.

Viton (US 3094)[1]

The data in Table II show a slight loss in weight and volume as a result of high temperature and as a result of immersion in Shelldyne H. This loss of plasticizer (which was used for compounding purposes and not for tailoring of the product properties) is accompanied by small increases in tensile strength and hardness and by a small decrease in elongation. The data (see Table B.1) stabilized quickly with time, indicating that the changes noted are not progressive in nature.

The basic Viton AHV material appears to be compatible with Shelldyne H at room temperature and at 160°F.

[1]Material construction designations of Uniroyal Rubber Company.

Table II. Average Immersion Test Results, Nonmetals.

Material	Storage Temperature (°F)	Tensile Strength (psi)	Elongation (percent)	Modulus (psi x 10^{-3})	Volume Change (percent)	Weight Change (percent)	Shore A-2 Hardness
Viton (US 3094)	70[a]	1,160	768	–	-1	-0.2	55
	70	1,350	738	–	-5	-1.9	57
	160[a]	1,500	694	–	-2	-1.1	57
	160	1,810	615	–	-4	-1.7	59
Viton/Nomex (US 941)	70[a]	4,560	26	–	-5	0.1	35
	70	5,030	32	–	-2	1.5	86
	160[a]	4,630	26	–	-1	-0.5	83
	160	5,650	29	–	-1	1.1	86
Nitrile (US 3010)	70[a]	1,390	288	–	5	0.1	61
	70	1,300	296	–	10	12.1	54
	160[a]	1,390	222	–	1	-1.4	63
	160	830	178	–	29	22.5	56
Nitrile/Nylon (US 566 RL)	70[a]	7,170	42	–	2	-0.6	82
	70	7,070	43	–	4	8.6	78
	160[a]	7,440	45	–	-1	-1.6	84
	160	7,540	43	–	13	12.8	89
EPT (US 3015)	70[a]	1,040	633	–	-1	0.6	51
	70	150	170	–	138	140	36
	160[a]	1,150	569	–	13	0.3	56
	160	50	125	–	217	223	19
Nylon	70[a]	7,150	67	32.8	-3	-0.4	–
	70	6,270	78	33.2	-1	1.4	–
	160[a]	10,660	42	47.2	-2	-2.7	–
	160	8,730	53	37.4	0	-0.1	–
Teflon	70[a]	2,770	398	15.3	1	0.0	–
	70	2,300	324	14.8	1	0.7	–
	160[a]	2,070	285	15.0	-1	0.0	–
	160	2,580	354	14.8	1	0.4	–
Silicone Rubber	70[a]	720	268	–	-2	[illegible]	52
	70	460	210	–	18	16.1	47
	160[a]	730	275	–	0	-0.1	53
	160	540	243	–	30	22.5	46

[a]Control samples not immersed in Shellovne H.

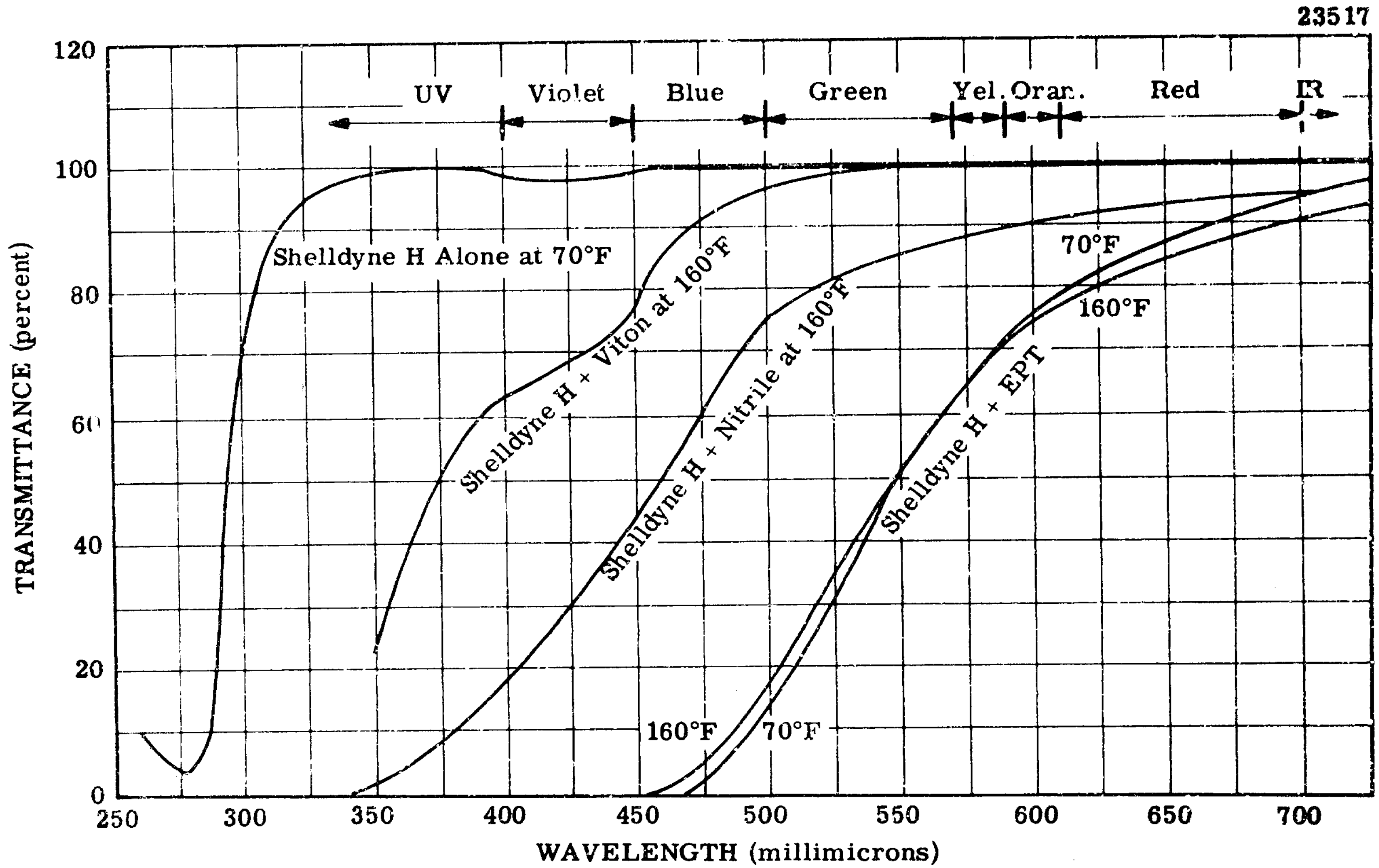

Figure 1. Light Transmittance Versus Wavelength, Shelldyne H after Contact with Elastomers.

Nitrile (US 3010)[1]

The data in Table II indicate significant swelling and weight gain as a result of immersion in Shelldyne H. This fuel absorption is also accompanied by softening of the rubber and by some loss in tensile strength.

Ethylene Propylene Termpolymer (EPT, US 3015)[1]

The data in Table II show a basic incompatibility of EPT with Shelldyne H. Fuel absorption degraded the rubber until virtually all of its tensile strength was gone. The elongation and hardness of immersed EPT are only fractions of their original values.

Silicone Rubber

As a result of immersion, the silicone rubber has absorbed a significant amount of fuel, softened, and has lost tensile strength and elongation. These changes have apparently stabilized with time and do not appear to be progressive.

Because it has attractive low- and high-temperature properties, silicone rubber was also considered as a structural material which may only be splashed or wet with fuel for very short time periods.

A series of tests was performed to determine the rate of absorption of Shelldyne H by silicone rubber. Strips of silicone rubber were immersed in Shelldyne H at room temperature for varying periods of time, and the weight increases of the samples were noted. These data are shown in Figure 2. It is apparent that the absorption occurs very rapidly, with a 10 percent weight increase noted after one hour of immersion. After 12 hours of immersion, the weight increase levels off at about 17 percent, the equilibrium absorption level at room temperature (see Table II).

Each of the samples, upon removal from the Shelldyne H, were allowed to dry under ambient conditions. For the particular sample configuration (1 by 6-inch dog bones, 0.05-inch thick, with one side at a time exposed to air, and with the sample turned over intermittently), and for the particular set of air conditions (temperature, relative humidity, air velocity), the rate of drying is approximated by:

$$-\frac{dc}{dt} = 0.3\,C$$

where

c = weight of absorbed fuel as a percent of the initial sample weight

t = drying time, days

What this relationship indicates is that half of the fuel evaporated every 2.3 days

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[1] Material construction designations of Uniroyal Rubber Company.

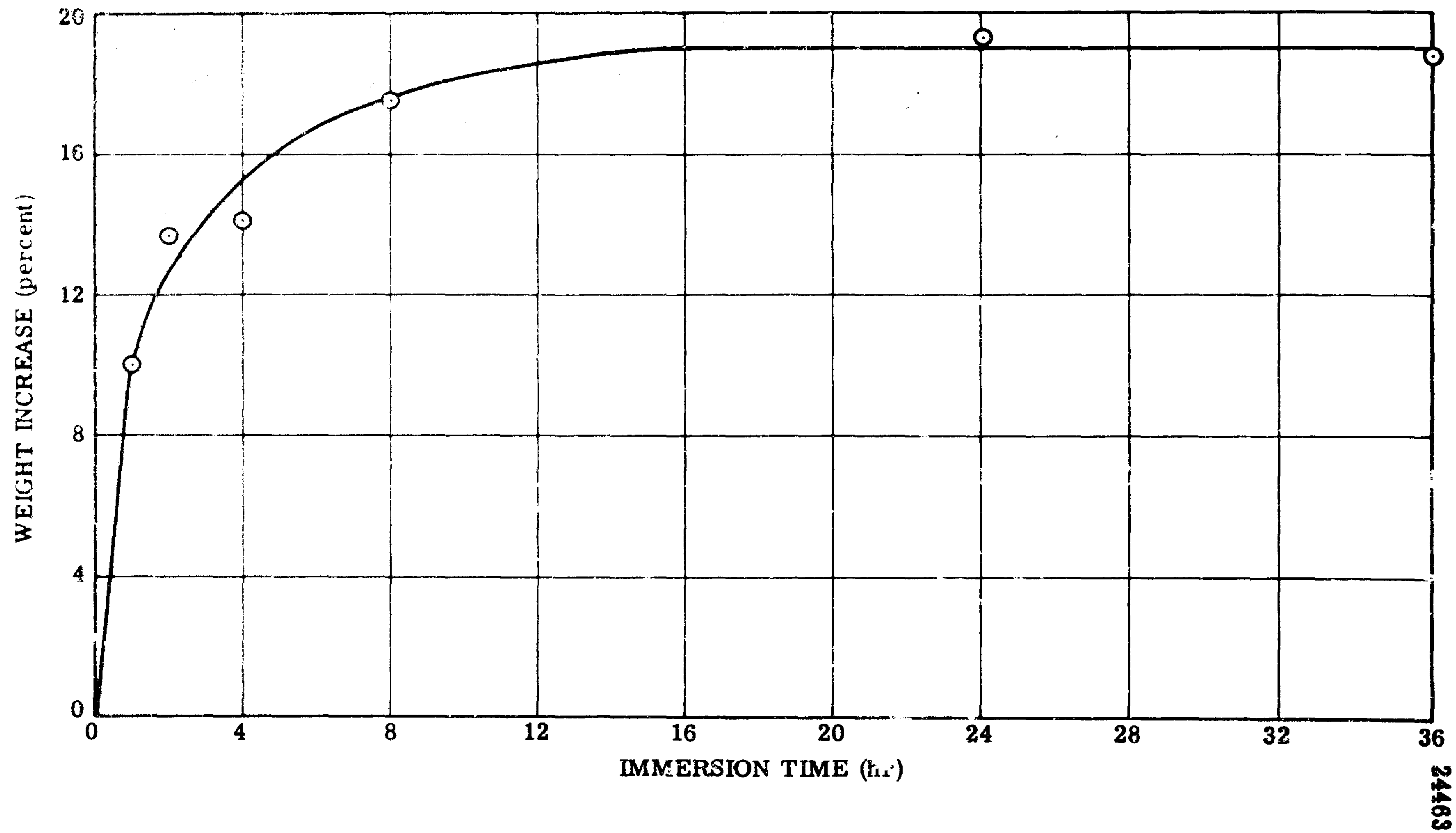

Figure 2. Limited-Time Immersion of Silicone Rubber.

This relatively low drying rate is due to the very low vapor pressure of Shelldyne H at room temperature. If silicone rubber in a ramjet fuel system had been wet with Shelldyne H, the drying time would be longer if the rubber were either in an enclosed space or at a lower temperature

When the silicone rubber samples had dried completely, their original properties were qualitatively regained. No apparent permanent change had occurred.

In view of the rapid fuel absorption rate and the low drying rate, silicone rubber that might be splashed or wet in a ramjet fuel system should be considered to remain wet. Hence, the dimensions, weight, and tensile strength of the wet silicone rubber should be considered for such a design application.

Nylon

The data in Table II show that the nylon specimens not immersed in Shelldyne H are somewhat temperature-sensitive. Probably as a result of a loss of moisture, nylon at 160°F showed a small volume and weight loss, accompanied by an increase in tensile strength and modulus and by a loss in elongation.

The nylon specimens immersed in Shelldyne H, compared to the control samples at the same temperature, show a small amount of fuel absorption with a small relative loss in tensile strength and gain in elongation. The 2 to 3 percent of Shelldyne H appears to plasticize the nylon.

Viton/Nomex (US 941)[1]

The Viton/Nomex construction consists of five layers, two Nomex (a high-temperature nylon) fabric layers, and three Viton AHV layers. The data in Table II indicate that this construction is affected only slightly by temperature or by immersion in Shelldyne H. The small increase in weight as a result of immersion is likely a balance between the decrease in weight observed with unreinforced Viton and the increase in weight observed with nylon. The tensile strength and elongation of the Viton/Nomex are relatively unaffected by immersion.

Nitrile/Nylon (US 566 RL)[1]

This composite material also exhibits the properties of its components. A significant amount of fuel was absorbed, but the tensile strength and elongation were unaffected (contrary to the behavior of nitrile above). The amount of fuel absorbed reached an equilibrium value very early, with no indication of any progressive change.

Teflon (TFE)

Table II indicates a small amount of Shelldyne H (less than 1 percent) had been absorbed by Teflon. This value is consistent with the absorption of other hydrocarbons by Teflon. However, this minor absorption had little if any effect upon the tensile strength, elongation, or modulus of the material. The control specimens at 160°F apparently underwent some annealing, lowering the tensile strength somewhat, but this change did not occur in the immersed specimens at 160°F.

Except for the minor fuel absorption, Teflon is compatible with Shelldyne H.

[1]Material construction designations of Uniroyal Rubber Company.

3. PERMEABILITY TESTS

Permeability was measured using Payne cups which hold approximately 15 milliliters of fuel. A specimen of elastomer 10 square centimeters is clamped between two flanges in the exposed surface area. Permeability is measured by the weight loss from the Payne assembly as a function of time.

Specific permeability is defined as the number of milligrams of Shelldyne H which has permeated through 1 square centimeter of film one millimeter thick in 24 hours at room temperature and pressure. The elastomer specimens used ranged between 0.5 and 1.2 millimeters in thickness.

Two Payne cups were prepared for each of the materials tested. Originally, the cups were oriented with the elastomer above the fuel (the "up" configuration), so that any loss of fuel might result in a vapor space adjacent to the elastomer. Once equilibrium permeation was established, one of each pair of cups was inverted (the "down" configuration) so that the fuel always wets the elastomer.

The specific permeability data are listed in Table III. The first observation made is that no significant differences were obtained between the "up" and the "down" configurations of the Payne cups.

The permeability rates through the unreinforced Viton, the Viton/Nomex, and the nitrile/nylon are relatively low, and there is some indication that the rates decrease with time. The permeability rate through unreinforced nitrile rubber was significantly higher. The rate through EPT was extremely large and, in fact, the EPT became wet through with fuel.

To determine permeability rates more accurately, duplicate 6-inch bladders of Viton, Viton/Nomex, and nitrile/nylon were fabricated, filled with Shelldyne H, and sealed. Permeability data will be recorded for the remainder of the program.

4. HIGH SHEAR TESTS

A. Description of the Apparatus

Candidate materials were tested under high shear conditions in Shelldyne H, using a turbopump simulator. This apparatus, initially designed and used by Atlantic Research Corporation under another Air Force contract, was modified to suit the needs of this program. The apparatus consists of a large diameter disk driven by an electric motor and drive, which delivers 5 horsepower to the shaft at 4,000 r/min. The high shear rate is generated between the perimeter of the rotating disk and the inner surface of a ring which holds samples of several materials.

A photograph of the assembled apparatus is shown in Figure 3. A system of adjustable studs enables the alignment of the drive with the disk shaft for high-speed rotational operation. Figure 4 shows the bearing end of the apparatus. The high-speed seal consists of a pressure-balanced and spring-loaded graphite seal which bears upon a polished chrome-plated rotating surface. Also shown in Figure 4 is a 24-tooth counter gear which, in conjunction with the pickup transducer, provides an accurate measure of revolutions per minute.

Table III. Specific Permeability.

Material	Sample	Thickness		Specific Permeability[a] (after days in test)					Average
		Inch	Milimeter	45	75	105	135	165	
Viton	1	0.048	1.22	0.24 U	0.18 U	0.16 U	0.16 U	0.23 U	0.19
	2	0.048	1.22	0.19 U	0.07 U	0.13 D	0.10 D	0.12 D	0.12
	Average	0.048	1.22	0.22	0.13	0.15	0.13	0.18	0.16
Viton/Nomex	1	0.031	0.79	0.50 U	0.38 U	0.31 U	0.19 U	0.19 U	0.31
	2	0.031	0.79	0.10 U	0.00 U	0.08 D	0.01 D	0.05 D	0.05
	Average	0.031	0.79	0.30	0.19	0.20	0.10	0.12	0.18
Nitrile	1	0.036	0.91	0.80 U	0.98 U				0.89
	2	0.036	0.91	0.80 U	1.00 U				0.90
	Average	0.036	0.91	0.80	0.99				0.90
Nitrile/Nylon	1	0.019	0.48	0.18 U	0.17 U	0.10 U	0.06 U	0.08 U	0.11
	2	0.019	0.48	0.10 U	0.00 U	0.06 D	0.01 D	0.04 D	0.04
	Average	0.019	0.48	0.14	0.09	0.08	0.04	0.06	0.08
EPT	1	0.043	1.09	1.40 U	3.62 U				2.51
	2	0.043	1.09	1.80 U	4.23 U				3.02
	Average	0.043	1.09	1.60	3.93				2.77

U - Elastomer Up

D - Elastomer Down

[a]Specific Permeability Rate at STP $= \frac{\text{mg. loss} \times \text{min thickness}}{\text{sq. cm area} \times \text{days}}$

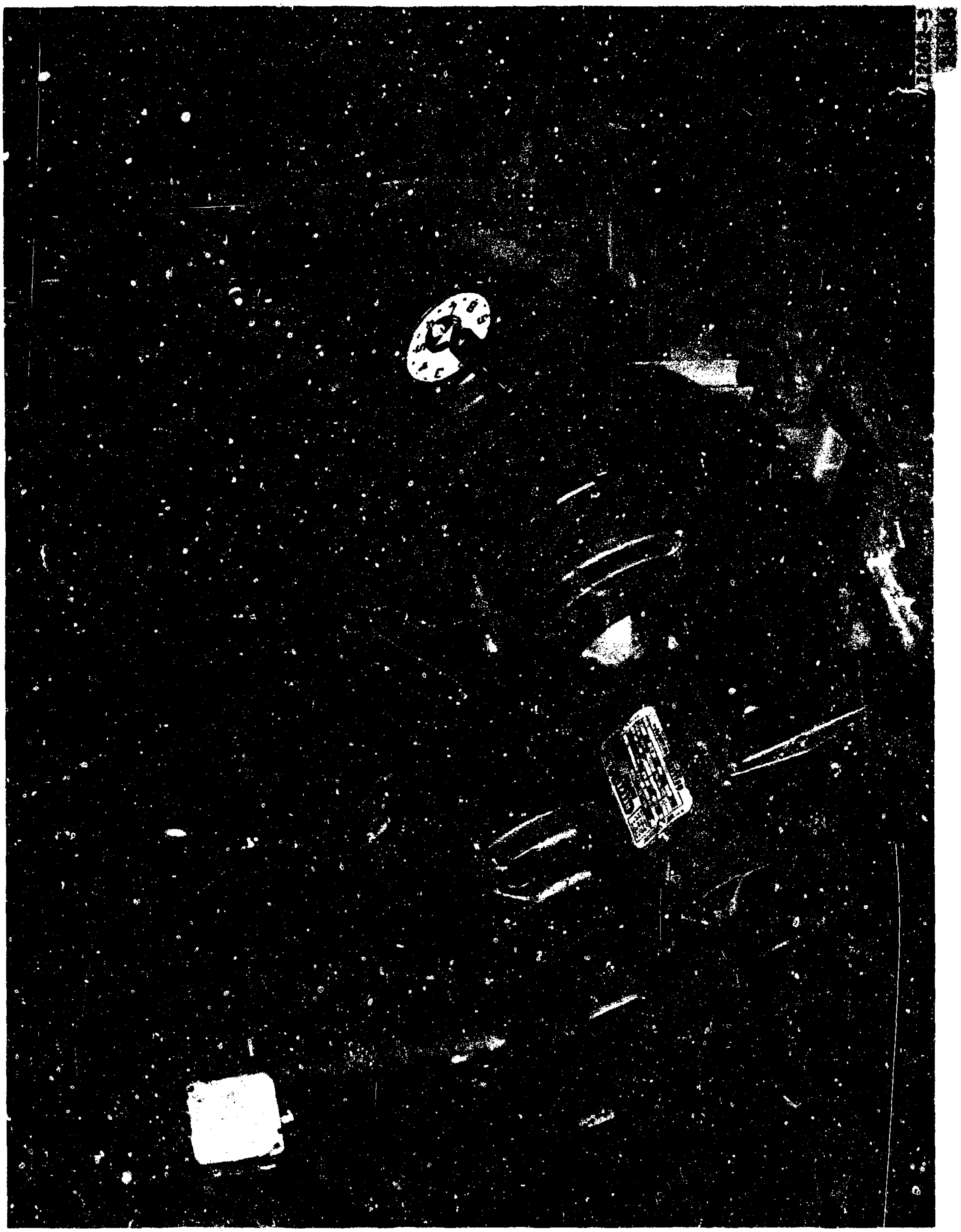

Figure 3. Pump Simulator, Overall View.

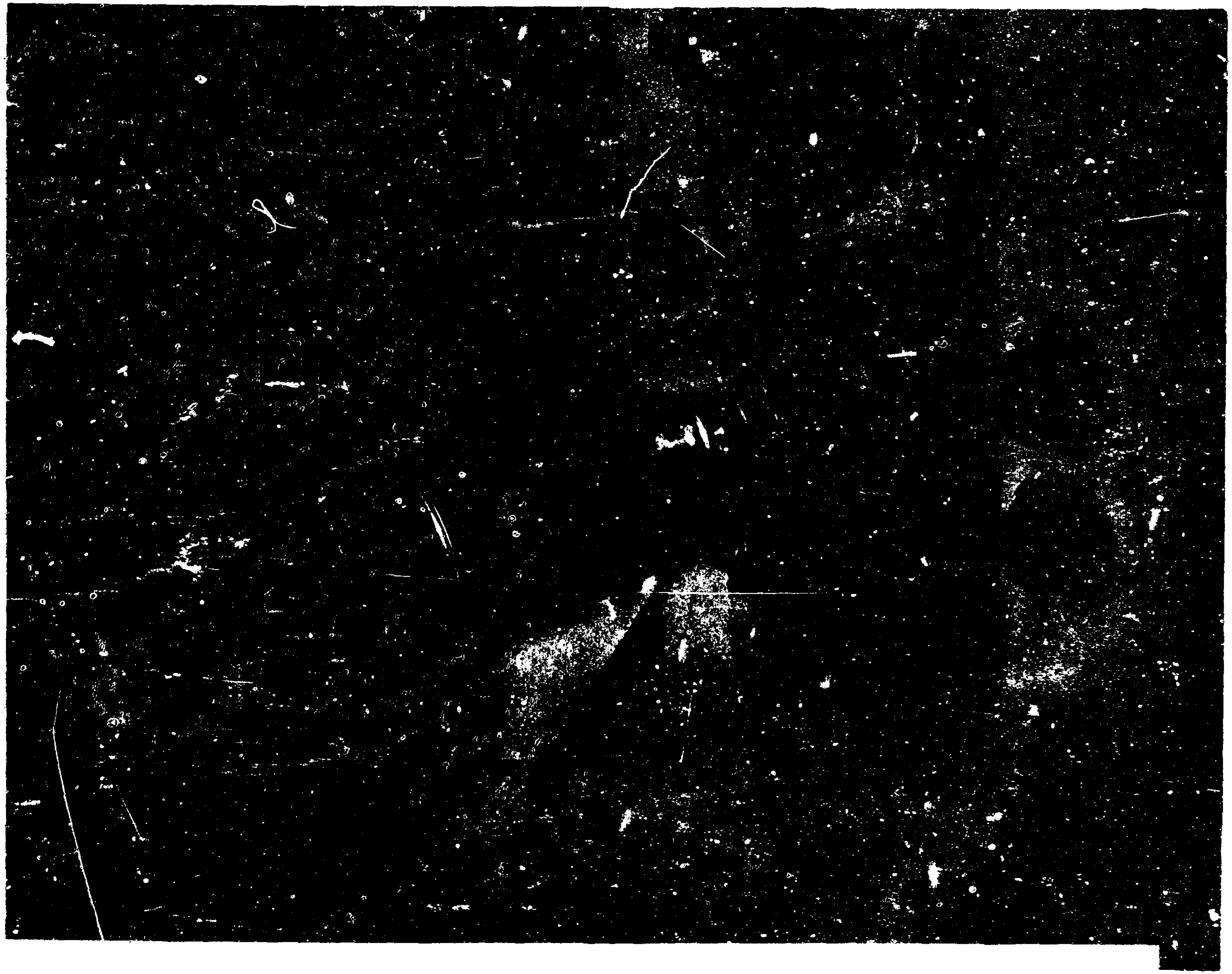

Figure 4. Pump Simulator, Showing Bearing and Counter Gear.

Figure 5 shows the opposite end of the apparatus. The cover plate, providing a static seal, is held by a snap ring, making it easily removable for inspection and replacement of samples. A thermocouple measuring fluid temperature is shown in Figure 5. Figure 6 shows the same end of the apparatus with the cover plate removed, exposing the rotating disk and the sample ring.

Figure 7 shows the sample ring with six different material samples bonded into place (with an epoxy cement). Proceeding clockwise in Figure 7, and starting with the white sample, the materials were Teflon, nylon, Viton (US 3094), Viton/Nomex (US 941), nitrile/nylon (US 566 RL), and silicone rubber.

B. Shear Rate

The rate of shear between two coaxial cylinders with relative rotation is

$$S = \frac{2 D_1 D_2 w}{D_2^2 - D_1^2} = \frac{\pi}{15} \frac{D_1 D_2 f}{D_2^2 - D_1^2}$$

where

S = shear rate, seconds^{-1}

D_1 = smaller diameter

D_2 = larger diameter

w = angular velocity, seconds^{-1}

f = angular frequency, r/min

For the pump simulator, D_2, the inside diameter of the sample ring is 7.50 inches. The rotating disk used had $D_1 = 7.20$ inches, resulting in a clearance of 0.15 inch. The shear rate as a function of frequency is then

$$S = 2.57 f$$

The drive is capable of rotational speeds to 8,000 r/min so that the range of shear rates available (with this particular disk) is up to 2.06×10^4 sec^{-1}. Another disk which has been designed has an outer diameter of 7.46 inches, a clearance of 0.02 inch, and a maximum shear rate of 1.56×10^5 sec^{-1}.

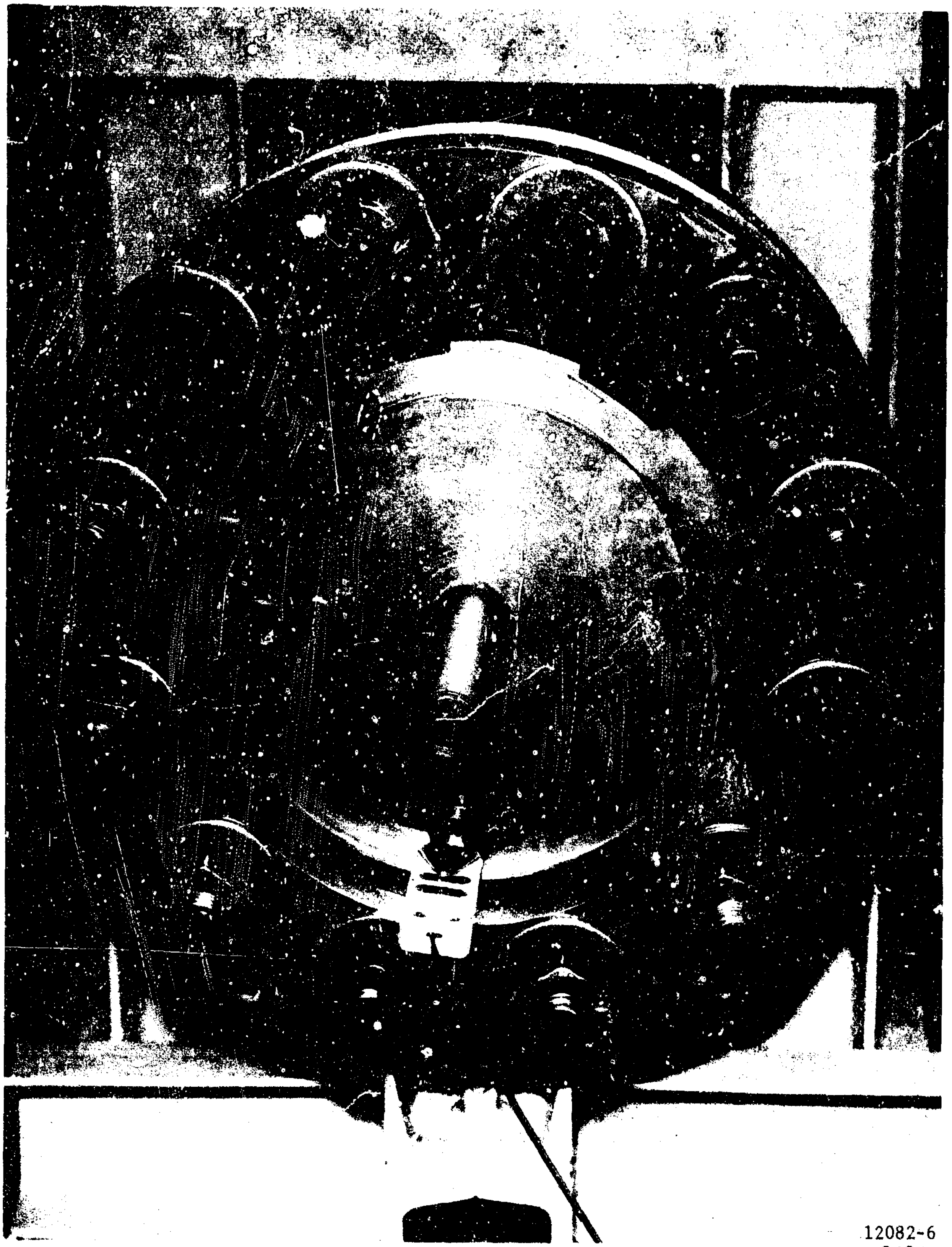

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Figure 5. Pump Simulator, Showing End Cover Plate.

Figure 6. Pump Simulator, with Cover Plate Removed.

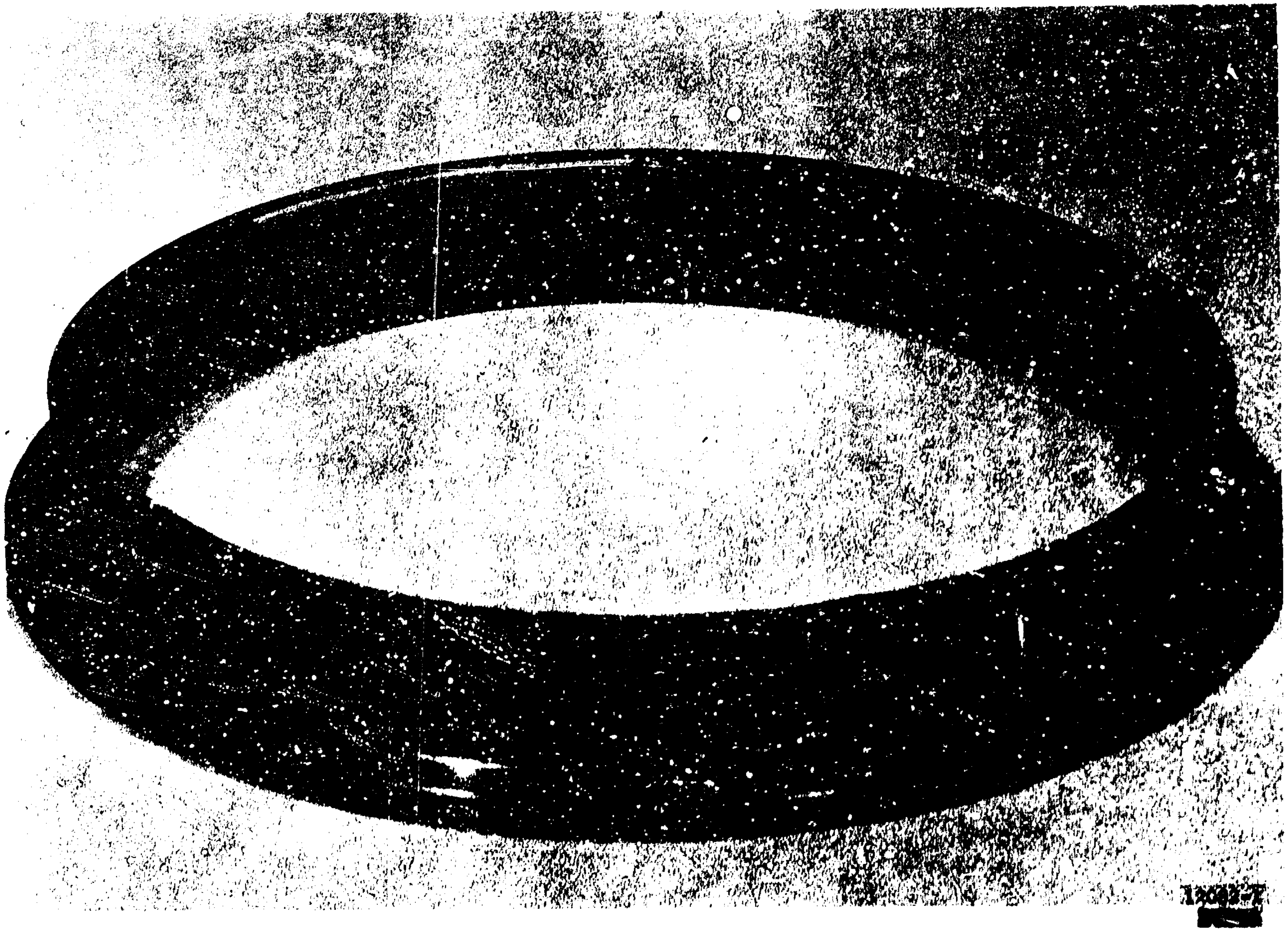


Figure 7. Pump Simulator Sample Ring.

C. Testing Performed

The pump simulator apparatus was assembled and filled with Shelldyne H. A bleed hole at the top of the apparatus permitted complete filling to occur For these tests, a standpipe was constructed from one of the ports, and a positive liquid head of about 6 inches was maintained during the tests. The other port accommodated a thermocouple which measured the fuel temperature. A small flow of cooling water was maintained on the outside of the apparatus between the two large flanges.

Two tests were conducted, each of 90 minutes duration. For Test 1, a rotational speed of 3,910 ± 10 r/min was maintained, resulting in a shear rate between the disk and the material samples of 1.003 ± 0.003 x 10^4 sec^{-1}. The apparatus performed well for this extended duration. At the end of Test 1, the cover plate and the sample ring were removed, and the material samples were examined. There was no evidence of any erosion or wear for any of the six materials as a result of the high shear environment in Shelldyne H.

The apparatus was then reassembled, using the same sample ring, and Test 2 was performed for 90 minutes. The rotational speed was 3,930 ± 10 r/min, resulting in a shear rate of 1.009 ± 0.003 x 10^4 sec^{-1}. Again, no mechanical problems resulted. When the sample ring was removed after Test 2, it was discovered that the bond holding the silicone rubber sample to the steel ring had failed and that a corner of the silicone rubber sample was torn. The rubber itself, however, as well as the other five materials, showed no evidence of degradation or failure because of the high shear environment.

The initial fuel temperature prior to Test 1 was 52°F. Once the test began, the temperature rose sharply, reaching 95°F after 1 minute of operation. After 15 minutes, the temperature reached 150°F, and the temperature stabilized at 153 to 156°F for the remainder of the test. At the start of Test 2, the temperature was 75°F, rising to 107°F after 1 minute, 152°F after 15 minutes, and stabilizing at 150 to 153°F for the remainder of the test.

The two tests performed resulted in four major conclusions. First, there was no evidence of erosion or other degradation for any of the six materials as a result of a high shear environment in 150°F Shelldyne H for 3 hours of operation. Second, the graphite seal on the apparatus performed well while in contact with 150°F Shelldyne H, indicating that similar turbopump seals and bearing surfaces are suitable for use with Shelldyne H. Third, the teardown, inspection, and reassembly of the apparatus between Tests 1 and 2 consumed 38 minutes, proving the value of the equipment revision, especially for Task II testing. Fourth, the successful operation of the revised pump simulator assembly for a very extended time period (180 minutes) served as a severe checkout for Task II testing.

5. VIBRATION AND FLEXING TESTS

Another testing sequence accomplished was the vibrational and flexing tests of candidate elastomers and plastics while immersed in Shelldyne H at 160°F. The specimens consisted of 1- by 6-inch strips of Viton, Viton/Nomex, nitrile/nylon, nylon, and Teflon. All except the nylon were in the shape of ASTM tensile-testing dog bones.

The experimental setup consisted of a shaker connected to the top of each of the specimens with a vertical rod and five clamps. The specimens were suspended in a beaker of Shelldyne H which was, in turn, heated in a water bath (using a hotplate) to 160°F. At the bottom end of each specimen was a 15-gram weight, so that a flexing action would be promoted according to the table below:

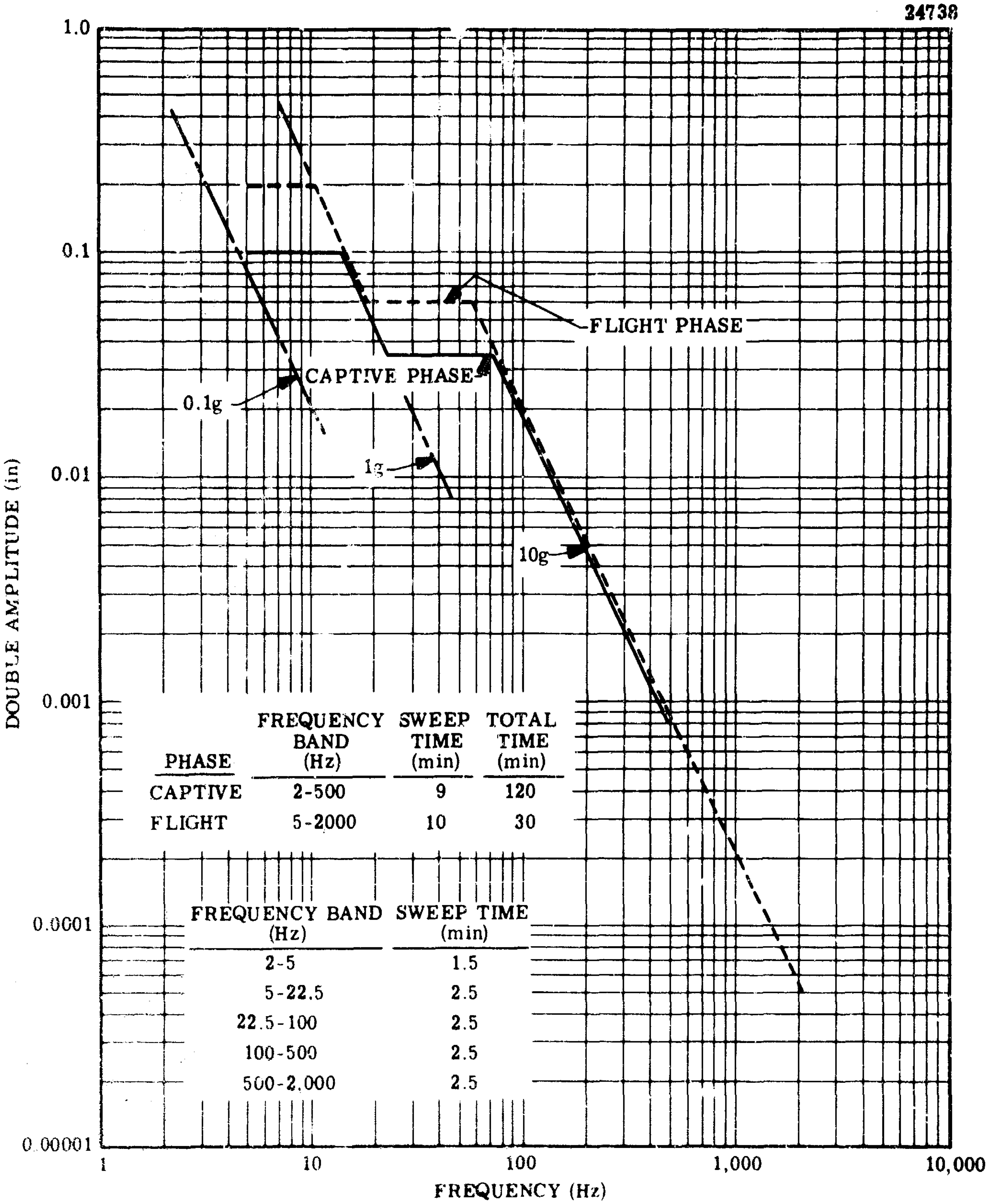
	10g Acceleration	
Material	Stress (psi)	Strain (percent)
Viton	13.6	4.8
Viton/Nomex	21.0	0.21
Nitrile/Nylon	34.2	0.17
Nylon	4.4	0.01
Teflon	10.7	0.08

The vibrational schedule followed is shown in Figure 8. This schedule was abstracted from MIL-STD-810B (15 June 1967), Method 514, Category (d), "Air-Launched Vehicle." Two tests were performed as shown in Figure 8: a captive phase (corresponding to aircraft carriage) of 120 minutes duration, and a missile flight phase of 30 minutes duration. The frequency was set with a wide range oscillator and the amplitude was adjusted with a power amplifier to the electromagnetic shaker. Two types of measurements were taken in different ranges to set the amplitude of oscillation. At the lower frequencies, the double amplitude was directly measured using a pointer and a scale. At the higher frequencies, where the amplitude was too small to measure, an accelerometer mounted on the shaker was monitored on an oscilloscope to enable the g-level to be set.

In this way, the schedule shown in Figure 8 was realized. The total number of cycles in each of the two phases was on the order of 1.2 million.

Following these two vibration and flexing tests, the specimens were weighed and tensile tested:

Material	Weight Change (percent)	Tensile Strength (ksi)
Viton	-0.6	1.33
Viton/Nomex	-0.1	4.60
Nitrile/Nylon	+4.5	6.27
Nylon	+0.5	7.82
Teflon	+0.4	1.90



PHASE	FREQUENCY BAND (Hz)	SWEEP TIME (min)	TOTAL TIME (min)
CAPTIVE	2-500	9	120
FLIGHT	5-2000	10	30

FREQUENCY BAND (Hz)	SWEEP TIME (min)
2-5	1.5
5-22.5	2.5
22.5-100	2.5
100-500	2.5
500-2,000	2.5

Figure 8. Vibration Testing Schedule Compiled from MIL-STD-810B (15 June 1967) Air-Launched Vehicle.

It is apparent that these values are not significantly different from the values reported for the immersion tests. In conclusion, then, the vibration and flexing in a hot Shelldyne environment did not degrade the properties of any of the materials tested.

6. HOT PRESSURANT GAS TESTS

The double-chamber rocket motor shown in Figure 9 was used to conduct four tests of candidate bladder materials in a solid propellant gas generator exhaust gas environment. The second (test) chamber duplicates typical fuel system pressures to obtain realistic specimen heating rates.

The primary chamber contained an end-burning, 6-inch-diameter grain of a solid gas generator propellant, and was vented through a sonic nozzle into the secondary or test chamber which contained the simulated fuel bladder. The secondary chamber nozzles were sized so that the pressure would be maintained at 300 to 400 psia.

The simulated bladder in the test chamber consisted of a 1-inch tubing cross which was completely filled with Shelldyne H. Each of the four ends of the cross was sealed with a 1-inch-diameter disk of a candidate bladder material. From the viewpoint of the elastomer specimen, then, the environment was the same as in a fuel system bladder, with hot gases on one side and fuel on the other side. For each test, one specimen was unreinforced Viton (0.048 inch thick), one specimen was a double layer of nitrile/nylon (each ply 0.019 inch thick), and two specimens were Viton/Nomex (0.031 inch thick).

Two Atlantic Research gas generator solid propellants were used. For the first two tests, a CTPB binder system propellant, ARCADENE® 242, was used. The theoretical flame temperature of this propellant is 1,984°F, with corrosive HCl comprising 8.6 percent (by volume) of the exhaust gases. The propellant used for the last two tests was ARCITE® 479F, a PVC binder system propellant with a theoretical flame temperature of 2,003°F, and with 17.0 percent HCl in the exhaust gases. Table IV lists the theoretically calculated properties of the exhaust gases for these two propellants.

Table V lists the test conditions and results for the four tests. Test chamber pressures and temperatures were measured for each test, and they differ somewhat from test to test. In addition, the solid propellant firing time varied among tests. A severity factor, S, for each test was calculated based upon the total heat flux to the specimens:

$$\text{Severity Factor} = \left(\frac{M}{\theta}\right)^{0.8} (T\text{-}1000)\,(\theta) = M^{0.8}\,\theta^{0.2}\,(T\text{-}1000)$$

where

θ = firing duration, seconds

T = measured gas temperature, °F

M = total propellant weight, pounds

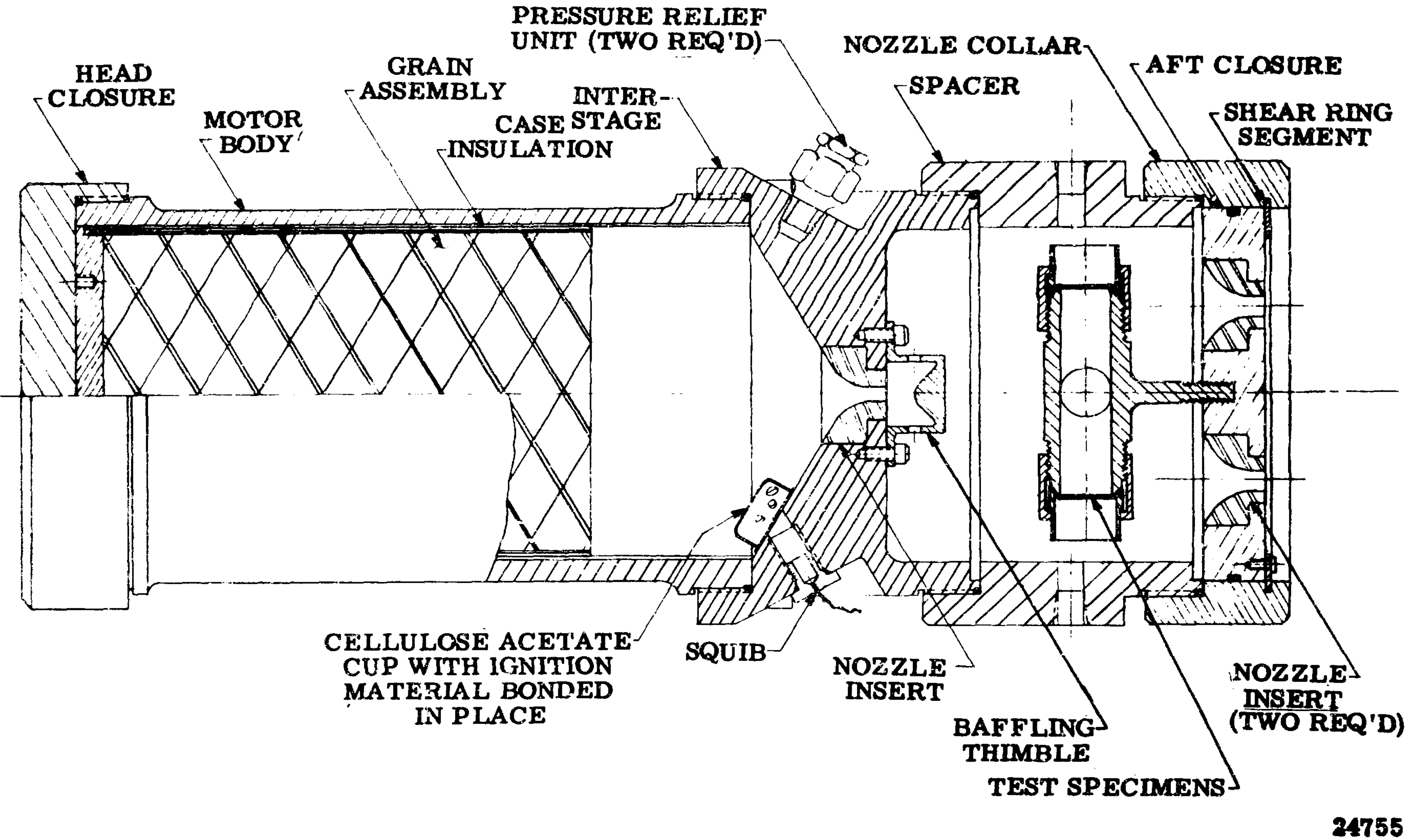


Figure 9. Gas Generator Test Motor.

Table IV. Theoretical Performance of Gas Generator Propellants, Chamber Pressure = 1,000 psia.

		ARCADENE 242	ARCITE 479F
Flame Temperature, °F		1,984	2,003
Gram Moles Total Gas/100 grams		4.828	4.404
Mole Fraction	CO	32.1	23.0
	CO_2	6.6	6.6
	HCl	8.6	17.0
	H_2	31.5	28.8
	H_2O	12.9	16.8
	N_2	6.5	6.6
	Total Solids	0.0	0.0

Table V. Gas Generator Compatibility Tests.

	Test 1	Test 2	Test 3	Test 4
Date	1-13-70	1-15-70	1-27-70	1-30-70
Gas Generator Propellant	ARCADENE 242	ARCADENE 242	ARCITE 479F	ARCITE 479F
Propellant Weight, lb	8.2	3.8	3.7	8.9
Firing Time, sec	12.6	5.8	9.5	19.1
Primary Pressure, psia	1,180	1,150	930	1,030
Test Chamber Pressure, psia	370	351	268	310
Test Chamber Temperature, °F	1,830	1,710	1,500	1,630
Condition of Specimens:				
Nitrile/Nylon (0.038 in.)	C	C	A	C
Viton (0.048 in.)	D	A	A	B
Viton/Nomex No. 1 (0.031 in.)	B	A	A	A
Viton/Nomex No. 2 (0.031 in.)	D	A	A	A

Note: A - Charred on outside, but specimen still intact without leaks or holes, elastomer pliable.

B - Charred through, causing leakage, elastomer pliable.

C - Charred through, causing leakage, elastomer hard (carbonized), no longer pliable.

D - Burned through completely without leaving residue.

The total heat flux varies directly with time and temperature during force (a nominal average specimen surface temperature of 1,000°F was assumed), and with the mass flow rate to the 0.8 power. The severity factor, then, for the four tests are:

Test	Severity Factor
1	7400
2	2900
3	2200
4	6500

On this basis, then, Test 3 was the least severe, and Test 1 was the most severe. The tabulated condition of the specimens (from Figure 3) bear out this ranking. In Test 3, all four specimens survived intact, with no burnthroughs. In Test 1, all four specimens failed. Tests 2 and 4 served to differentiate among the bladder materials according to their resistance to the thermal environment. In both tests, the double thickness of nitrile/nylon failed. In Test 4, the unreinforced Viton failed. Both Viton/Nomex specimens remained intact, however, for both Tests 2 and 4.

On the basis of these tests, the Viton/Nomex composite material is the clear choice for superior resistance to a hot gas environment. It might be added that this result was obtained despite the fact that the Viton/Nomex was the thinnest of the three materials tested.

Observation of the Viton/Nomex specimens indicated that the Nomex fabric acted as an effective heat barrier, since the char layer did not extend past the fabric.

7. LOW TEMPERATURE MECHANICAL PROPERTIES

Since the fuel system simulator must perform its delivery function at -65°F, the elastomers used for the bladder material and for seals must not embrittle at -65°F, and must retain sufficient flexibility to function in an acceptable manner.

Nitrile rubber is a copolymer of butadiene and acrylonitrile. As the acrylonitrile content is decreased, the low temperature flexibility of the rubber is increased, but at the expense of resistance to oils, fuels, and elevated temperatures. With proper compounding, nitrile rubber retains sufficient flexibility at -65°F so that it is commonly used for this low temperature service.[1]

Silicone rubber possesses excellent resistance to temperature extremes. Flexibility has been demonstrated at -175°F, and the normal maximum service temperature for sustained periods is 500°F. Fluorosilicone elastomers have flexibility at -65°F and are resistant to many fuels and oils.[1] However, the silicones and fluorosilicones have much poorer tensile strengths than other elastomers; it is difficult to effectively reinforce these rubbers because of poor adhesion properties and high permeability rates.

[1] Parker Seal Company.

Viton has outstanding resistance to fuels and oils, and is useful to extremely high temperatures. Its low temperature properties are not as attractive as those of some other elastomers, but Viton, through proper compounding and component design, can be used at -65° F.

Time-honored flexibility tests of O-rings indicate a minimum usable temperature of -40 to -50° F for Viton. However, these tests are based on the ease of flexing over a given size mandrel. Most elastomers become hard and brittle, and break and shatter in the flexing test when they reach their minimum usable temperature. Viton merely becomes stiff. Tests at -65° F conducted by F.H. Pollard of Republic Aviation Corp. (SAE Journal, May 1959) resulted in successful sealing by Viton.

General Dynamics concluded that F-111 wing cavity fuel cells made of Viton materials were good for severe flexing and wrinkling in the -35° F to -40° F range and for moderate flexing at -65° F.

Teflon, in addition to its inert character, possesses excellent low and high temperature mechanical properties. The main drawbacks are cold flow, the necessity for using thin sections to achieve flexibility, relatively poor tear resistance, the difficulty in fabrication and bonding, and high cost.

Ethylene propylene terpolymer (EPT) has good low temperature flexibility, but it is basically incompatible with hydrocarbons.

In order to document the low temperature mechanical properties of the specific materials under study in this program, a series of low-temperature tests were conducted on US 941 (Viton/Nomex construction), US 566 RL (nitrile/nylon construction), US 3094 (unreinforced Viton), US 3015 (unreinforced EPT), and Teflon (TFE). The first was a qualitative test of immersing a strip of material in a dry ice methyl ethyl ketone (MEK) bath and attempting to bend the strip 180 degrees upon itself. At -85° F, the nitrile/nylon and the Teflon performed successfully, but the EPT, the Viton and the Viton/Nomex both cracked. At -65° F, all five materials were bent double without cracking.

Quantitative tensile tests were performed on these materials as a function of temperature. Table VI lists the data obtained for US 3094 (unreinforced Viton) and for US 3015 (unreinforced EPT); Table VII lists the data for US 941 (Viton/Nomex) and for US 566 RL (nitrile/nylon); and Table VIII lists data interpolated from values published by the Du Pont Company for Teflon (TFE). In addition to the measured rupture stress and rupture strain, Tables VI, VII, and VIII list the rupture stress reduced to an arbitrary 73° F reference temperature according to Smith:[1]

$$\text{Reduced Rupture Stress} = \frac{T_o}{T} \times \text{Rupture Stress}$$

where

T = test temperature, °R

T_o = reference temperature = 533° R

[1] T.L. Smith, "Ultimate Tensile Properties of Elastomers. II. Comparison of Failure Envelopes for Unfilled Vulcanizates," Journal of Applied Physics 35, 1, pp. 27-35, January 1964.

Table VI. Tensile Properties of Unreinforced Materials at Varying Temperatures.

Test Temperature (°F)	US 3094 (Viton) Rupture Stress (psi)	US 3094 (Viton) Rupture Stress Reduced to 73°F (psi)	US 3094 (Viton) Rupture Strain (percent)	US 3015 (EPT) Rupture Stress (psi)	US 3015 (EPT) Rupture Stress Reduced to 73°F (psi)	US 3015 (EPT) Rupture Strain (percent)
165	492 474	420 404	471 466	488 422	416 360	401 403
Average	483	412	468	455	388	402
73	1,588 1,535 1,508	1,588 1,535 1,508	698 690 732	1,807 1,807 1,692	1,807 1,807 1,692	685 687 608
Average	1,544	1,544	707	1,769	1,769	660
0	2,928 2,631	3,399 3,055	403 364	2,451 2,381	2,846 2,764	495 480
Average	2,780	3,227	384	2,416	2,805	488
-20	3,510 3,506	4,258 4,253	231 260	2,783 2,605	3,376 3,160	444 423
Average	3,508	4,256	246	2,694	3,268	434
-45	3,686 3,455	4,744 4,447	86 109	2,824 2,647	3,634 3,407	330 319
Average	3,570	4,596	98	2,736	3,520	324
-65	3,782 3,760	5,113 5,084	24 35	2,950 2,993	3,988 4,047	289 240
Average	3,776	5,098	30	2,972	4,018	264

Table VII. Tensile Properties of Reinforced Materials at Varying Temperatures.

Test Temperature (°F)	US 941 (Viton/Nomex) Rupture Stress (psi)	US 941 (Viton/Nomex) Rupture Stress Reduced to 73°F (psi)	US 941 (Viton/Nomex) Rupture Strain (percent)	US 566 RL (Nitrile/Nylon) Rupture Stress (psi)	US 566 RL (Nitrile/Nylon) Rupture Stress Reduced to 73°F (psi)	US 566 RL (Nitrile/Nylon) Rupture Strain (percent)
165	3,253	2,770	18			
	3,333	2,240	18			
	3,500	2,990	15			
Average	3,362	2,870	17			
73	4,395	4,395	14			
	4,124	4,124	17			
	4,244	4,244	17			
Average	4,254	4,254	16			
0	5,263	6,110	–			
	6,053	7,020	11			
	5,479	6,340	15			
Average	5,598	6,490	13			
-20	6,603	8,000	10			
	7,763	9,410	17			
Average	7,183	8,700	14			
-45	10,134	13,020	11			
	9,698	12,460	14			
	10,563	13,570	14			
Average	10,123	13,010	13			
-65	11,781	15,900	7	9,910	13,370	18
	10,875	14,670	7	10,910	14,710	17
	11,333	15,300	7	10,091	13,600	18
Average	11,329	15,300	7	10,304	13,900	16

Table VIII. Tensile Properties of Teflon (TFE) at Varying Temperatures (Calculated from Data in December 1964 Issue of the Journal of Teflon).

Temperature (°F)	Rupture Stress (psi)	Rupture Stress Reduced to 73°F (psi)	Rupture Strain (percent)
165	2,870	2,450	367
73	3,600	3,600	282
0	4,230	4,900	230
-20	4,400	5,330	215
-45	4,620	5,940	198
-65	4,810	6,500	184

The rupture stress is shown as a function of temperature in Figure 10, and the rupture strain is shown as a function of temperature in Figure 11. Figure 11 shows that both ethylene propylene terpolymer (EPT) and Teflon retain well over 100 percent elongation at -65° F, confirming the qualitative bending test previously discussed. Unreinforced Viton loses elongation rapidly at lower temperatures, but there is still 30 percent elongation at -65° F. These data confirm the fact that Viton stiffens but does not embrittle at this temperature. The Viton/Nomex composite suffers a sharp drop in elongation below -45° F, but there still is almost half the elongation at -65° F the material has at room temperature. The one point for the nitrile/nylon composite confirms the fact that this construction is much more flexible than the Viton/Nomex construction at -65° F.

The reduced rupture stress plotted against rupture strain in Figure 12 defines a Smith Failure Envelope for each material. Any combination of stress and strain to the right of each curve results in a failure of the material. Hence, failure will be averted if the component design limits the strain at a particular stress to the left of the curve.

The conclusion drawn from these data is that Viton and Viton/Nomex have limited flexibility at -65° F, but that these materials are not totally brittle so they could be useful in the proper configuration. Teflon, nitrile rubber, and EPT have greater flexibility than Viton at -65° F.

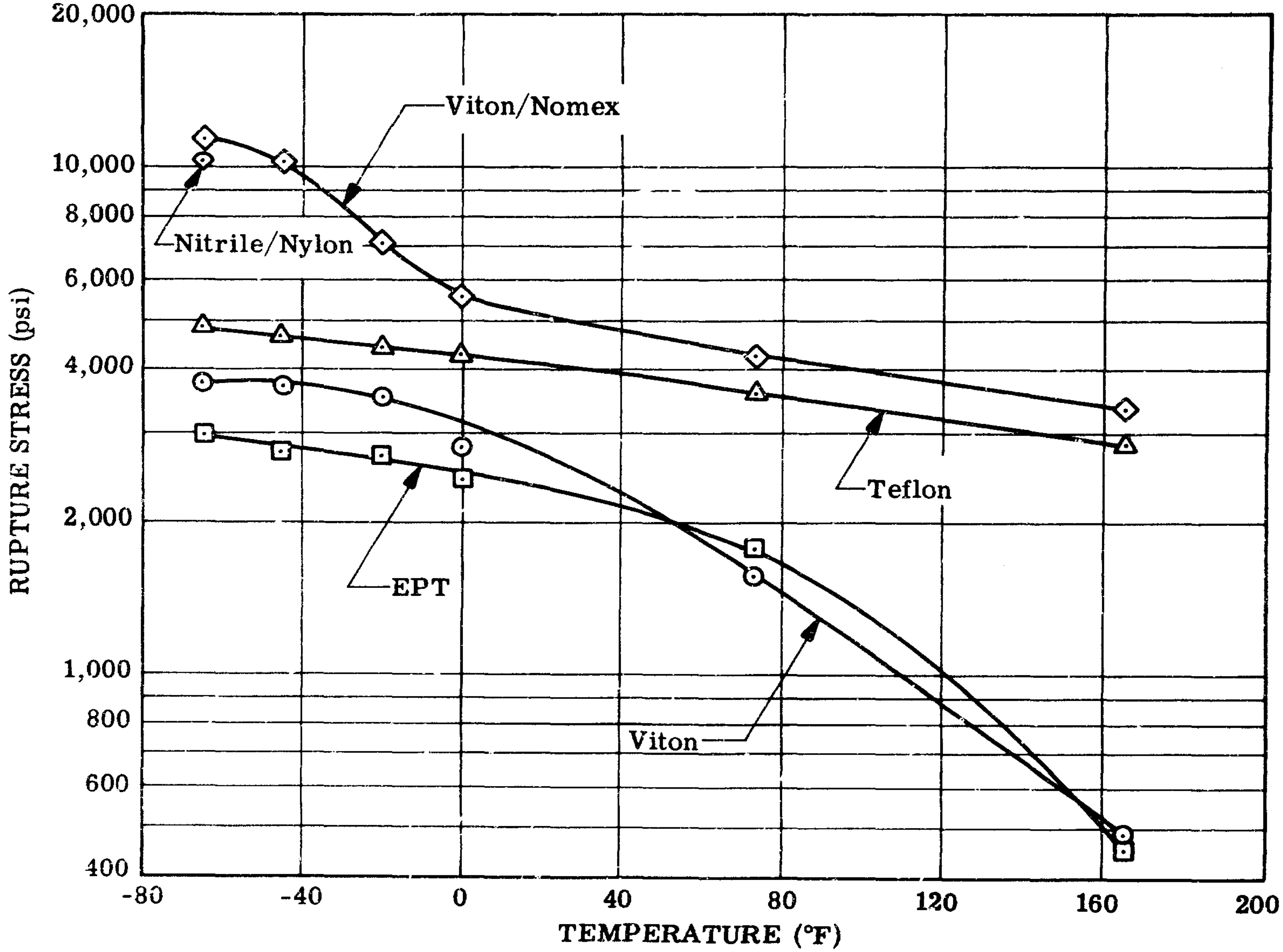


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Figure 10. Rupture Stress Versus Temperature.

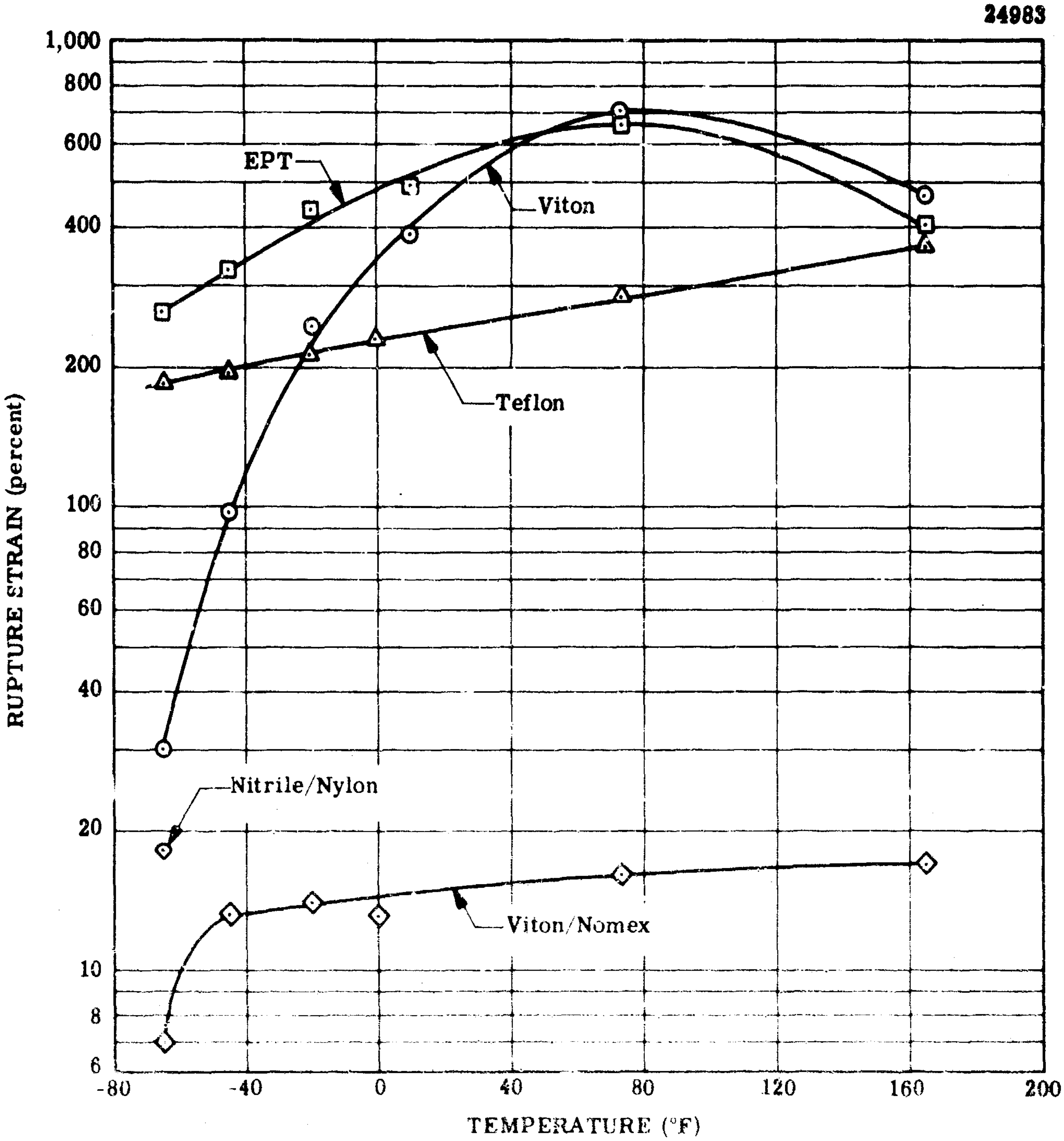

Figure 11. Rupture Strain Versus Temperature.

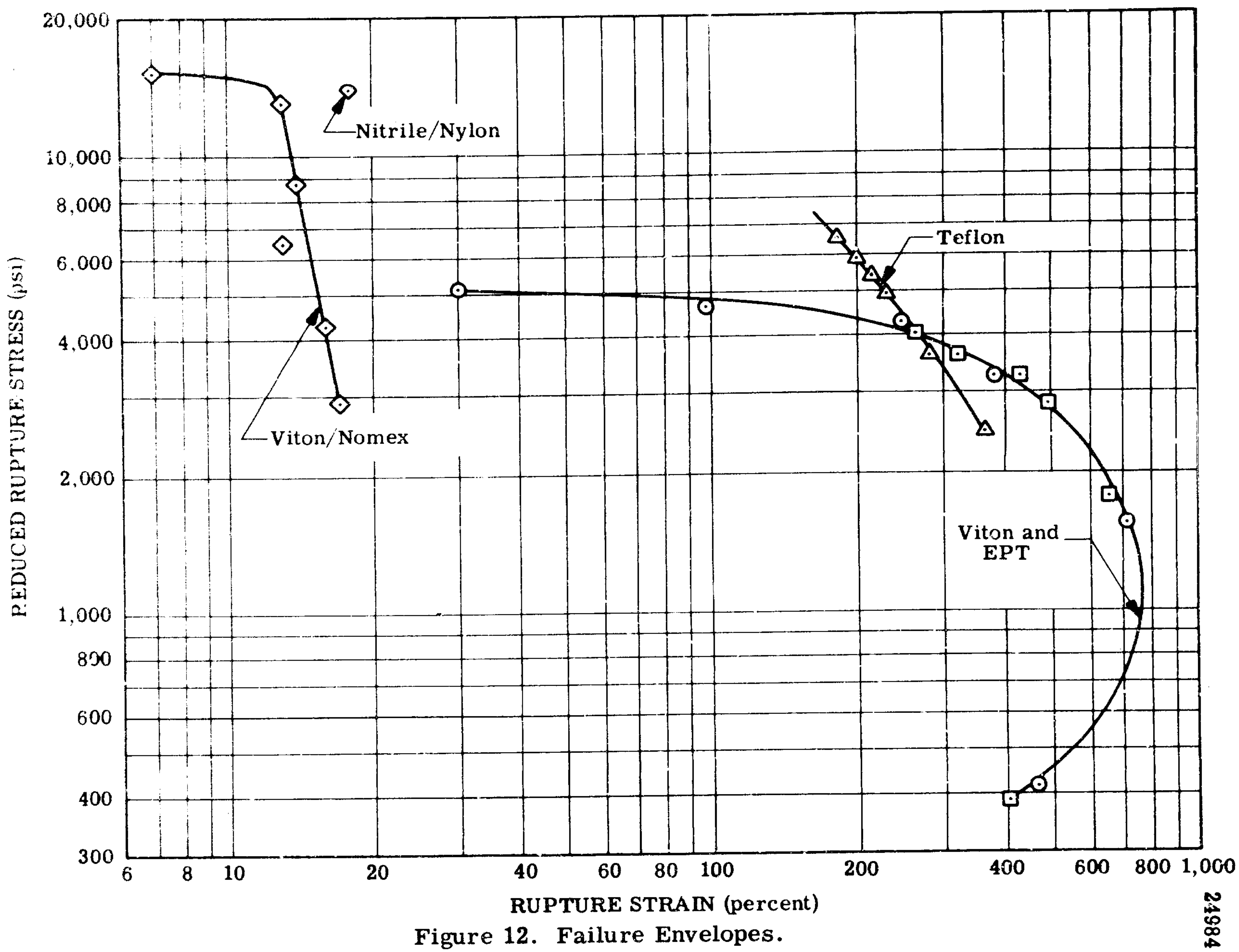

Figure 12. Failure Envelopes.

SECTION IV

SELECTION OF MATERIALS

1. SELECTED METALS

The eight metals (two steels, two stainless steels, two aluminums, and two titaniums) have all exhibited complete compatibility with Shelldyne H.

The metal selected for the fuel tank is 4130 alloy steel (which contains 0.95 percent Cr, 0.20 percent Mo, 0.30 percent C, and 0.50 percent Mo), in the normalized condition. This steel is superior in its fabricability since it is quite easy to roll, draw, and weld. The comparatively low cost of 4130 steel was an additional factor in its selection. The criteria of fabricability and cost are closely related, and it is in this area that 4130 offers a significant advantage over materials such as stainless steel and titanium, which are more expensive, or over an aluminum alloy which is more critical with respect to welding. Reduction of mechanical properties as a result of exposure to repeated moderate thermal test environments is not anticipated because of the use of 4130 steel in the normalized condition.

Other components of the fuel system simulator will be fabricated from steel, stainless steel, and aluminum. The standard pipe and tube fittings will be of steel and black iron (equivalent to steel in compatibility) because of the cost advantage, while special components such as the flowmeter, the quick-connect fittings, and the filters will be of stainless steel and aluminum.

A. Selected Bladder Materials

The primary bladder material selected is US 941, the Viton/Nomex construction. Although both Viton and Viton/Nomex have been shown to be compatible with Shelldyne H, the composite material has a much higher tensile strength and was shown to be the superior material from the standpoint of compatibility with hot pressurant gases. The rates of fuel permeability through both materials was shown to be acceptably low, and both have excellent high-temperature properties. Viton does not degrade up to 600° F. From 680 to 730° F, Viton has been used successfully for 30 to 40 hours, and it may be used for short periods of time up to 800° F.

The low temperature properties of Viton/Nomex (US 941) appear acceptable as it does not embrittle at -65° F. Based upon the excellent compatibility and high-temperature attributes, and upon encouraging low temperature measurements, this construction was the primary choice for a bladder material.

As secondary candidates for a bladder material, the nitrile/nylon construction (US 566 RL) and Teflon were selected. The nitrile/nylon elastomer, while retaining low permeability rates and high tensile strength, has absorbed a significant amount of fuel. Moreover, it is inferior to the Viton/Nomex composite in compatibility with hot pressurant gases. This material, however, exhibited superior low temperature flexibility which accounts for its selection as a backup material. Its low temperature suitability is at the expense of fuel resistance and of high-temperature resistance (the polymer tends to revert above 350° F).

Teflon, the other backup bladder material, has complete fuel compatibility as a virtue along with low temperature suitability. Teflon also has outstanding high-temperature usefulness, but it must be used in much thinner sections than elastomers for sufficient flexibility. This disadvantage would limit its usefulness with very hot pressurizing gases and would also present problems in tear resistance and tensile strength.

B. Other Nonmetals Selected

Based upon its compatibility with Shelldyne H, Viton has been selected as the primary O-ring and seal material. Although Viton becomes stiff at -65° F, it does not embrittle, and has been used successfully for sealing. As an alternate, nitrile rubber O-rings and seals will be used. The moderate swelling will be of advantage in sealing, and its good low temperature properties could prove invaluable.

Both nylon and Teflon have demonstrated excellent compatibility with Shelldyne H, so both these materials will be used. Teflon will find applicability as the lining in flexible tubing and as trim in selected fuel system components. Nylon, of course is the fabric reinforcement for the composite bladder material.

Silicone rubber will not be used where it might be wet with fuel, a direct result of the limited-time fuel immersion tests. EPT, being incompatible with Shelldyne H, will not be used.

APPENDIX A

IMMERSION TEST RESULTS FOR METALS

Table A.1. Immersion Test Results for 4130 Steel.

Storage Temperature (°F)	Days in T[illegible]	Tensile Strength (psi x 10^{-3})	0.2 Percent Yield Strength (psi x 10^{-3})	Modulus (psi x 10^{-6})
70[a]	40	70.6	–	24.4
		72.5	–	22.8
	159	68.7	45.3	29.7
		68.4	42.1	30.8
	Average	70.1	43.7	26.9
70	40	72.0	–	28.8
		72.1	–	25.1
	159	70.3	39.7	30.3
		68.4	42.6	26.3
	Average	70.7	41.2	27.6
160	40	73.7	–	32.0
		76.6	–	30.1
	69	70.0	42.9	24.6
		68.6	41.7	25.6
	96	69.6	44.5	28.1
		70.8	41.9	27.6
	159	67.3	41.6	27.6
		67.2	41.9	28.1
	Average	70.5	42.4	28.0

[a]Control samples not immersed in Shelldyne H.

Table A.2. Immersion Test Results for 4130 Steel (Cadmium Plated).

Storage Temperature (°F)	Days in Test	Tensile Strength (psi x 10^{-3})	0.2 Percent Yield Strength (psi x 10^{-3})	Modulus (psi x 10^{-6})
70[a]	26	69.4	–	30.3
		72.1	–	29.7
	145	66.2	42.4	28.1
		68.0	40.0	35.5
	Average	68.9	41.2	30.9
70	26	62.2	–	25.6
		63.0	–	25.5
	145	66.7	41.7	38.1
		67.2	–	–
	Average	64.8	41.7	30.1
160	26	67.0	–	37.5
		62.8	–	31.0
	55	66.2	40.0	31.9
		65.1	39.2	31.1
	117	62.9	40.8	33.4
		64.6	39.2	–
	145	67.0	41.9	–
		66.8	41.1	–
	Average	65.3	40.4	33.0

[a] Control samples not immersed in Shelldyne H.

Table A.3. Immersion Test Results for 321 Stainless Steel.

Storage Temperature (°F)	Days in Test	Tensile Strength (psi x 10^{-3})	0.2 Percent Yield Strength (psi x 10^{-3})	Modulus (psi x 10^{-6})
70[a]	40	88.4	–	–
		88.4	–	–
	159	77.6	31.2	25.3
		76.8	28.8	25.3
	Average	82.8	30.0	25.3
70	40	86.6	–	–
		86.8	–	–
	159	74.2	27.8	–
		79.9	27.9	23.5
	Average	81.9	27.9	23.5
160	40	81.0	–	26.3
		89.1	–	31.1
	69	–	29.1	27.7
		80.0	27.6	28.4
	96	75.3	27.8	22.8
		74.6	28.1	22.5
	159	79.4	30.0	22.4
		76.9	29.4	–
	Average	79.5	28.7	25.9

[a]Control samples not immersed in Shelldyne H.

Table A.4. Immersion Test Results for 14-8 Stainless Steel.

Storage Temperature (°F)	Days in Test	Tensile Strength (psi x 10^{-3})	0.2 Percent Yield Strength (psi x 10^{-3})	Modulus (psi x 10^{-6})
70[a]	47	132.4	–	36.6
		123.5	–	33.2
	166	126.7	53.3	32.0
		126.3	53.3	37.5
	Average	127.2	53.3	34.8
70	47	137.1	–	39.6
		135.0	–	38.6
	166	129.7	55.2	40.0
		125.0	53.3	40.0
	Average	131.7	54.3	39.6
160	47	139.3	–	41.1
		134.6	–	36.2
	76	133.7	52.0	36.7
		128.7	53.2	31.9
	138	129.8	54.8	–
		133.7	54.7	29.3
	166	127.7	55.0	33.3
		129.0	56.0	36.0
	Average	132.1	54.3	34.9

[a]Control samples not immersed in Shelldyne H.

Table A.5. Immersion Test Results for 7075 Aluminum.

Storage Temperature (°F)	Days in Test	Tensile Strength (psi x 10^{-3})	0.2 Percent Yield Strength (psi x 10^{-3})	Modulus (psi x 10^{-6})
70[a]	37	73.0	–	–
		82.7	–	–
	64	73.0	55.4	–
		–	–	–
	154	78.9	65.1	18.6
		75.8	59.7	16.7
	Average	76.7	60.1	17.7
70	37	82.7	–	–
		82.1	–	–
	154	75.7	64.3	19.7
		77.9	67.6	24.4
	Average	79.6	66.0	22.1
160	37	84.4	–	–
		85.1	–	–
	64	74.9	64.5	10.3
		76.5	64.9	13.8
	91	70.0	61.3	16.0
		76.1	63.3	17.8
	154	74.5	61.3	12.4
		74.2	61.1	13.7
	Average	77.0	62.7	14.0

[a]Control samples not immersed in Shelldyne H.

Table A.6. Immersion Test Results for 6061 Aluminum.

Storage Temperature (°F)	Days in Test	Tensile Strength (psi x 10^{-3})	0.2 Percent Yield Strength (psi x 10^{-3})	Modulus (psi x 10^{-6})
70[a]	46	47.7	–	–
		50.4	–	–
	75	40.3	35.1	12.8
		45.5	40.6	21.3
	165	43.3	39.4	17.0
		43.0	38.8	17.9
	Average	45.0	38.5	17.3
70	46	41.8	–	–
		45.2	–	–
	165	42.4	39.4	16.7
		42.1	38.2	19.7
	Average	42.9	38.8	18.2
160	46	37.7	–	–
		36.8	–	–
	75	43.9	38.8	13.3
		44.4	40.0	14.4
	137	42.7	39.4	18.2
		42.6	39.4	17.1
	165	42.6	40.0	20.6
		43.0	40.6	21.8
	Average	41.7	39.7	17.6

[a]Control samples not immersed in Shelldyne H.

Table A.7. Immersion Test Results for Titanium (6 Aluminum-4 Vanadium).

Storage Temperature (°F)	Days in Test	Tensile Strength (psi x 10^{-3})	0.2 Percent Yield Strength (psi x 10^{-3})	Modulus (psi x 10^{-6})
70[a]	61	166.8	–	–
		166.0	–	–
	180	167.7	156.0	34.8
		173.0	158.3	31.0
	Average	168.4	157.2	32.9
70	61	163.9	–	–
		163.5	–	–
	180	169.3	154.0	37.7
		167.0	153.3	30.0
	Average	165.9	153.7	33.9
160	61	164.5	–	–
		164.5	–	–
	90	166.1	148.4	32.9
		–	146.8	27.1
	117	164.0	143.1	36.0
		160.4	139.2	35.4
	180	168.3	152.7	36.0
		167.7	150.0	34.7
	Average	165.1	146.7	33.7

[a]Control samples not immersed in Shelldyne H.

Table A.8. Immersion Test Results for Titanium (5 Aluminum-2.5 Tin).

Storage Temperature (°F)	Days in Test	Tensile Strength (psi x 10^{-3})	0.2 Percent Yield Strength (psi x 10^{-3})	Modulus (psi x 10^{-6})
70[a]	46	138.5	–	23.1
		131.0	–	19.5
	165	140.8	119.4	41.1
		141.4	127.8	37.5
	Average	137.9	123.6	30.3
70	46	137.8	–	22.2
		137.0	–	25.4
	165	140.8	118.1	32.8
		135.9	114.1	32.2
	Average	137.9	116.1	28.2
160	46	137.8	–	19.6
		134.7	–	20.3
	75	146.5	124.4	34.7
		133.9	111.8	29.7
	137	140.3	118.1	30.0
		138.6	116.0	30.2
	165	146.3	122.0	31.1
		140.8	116.8	29.2
	Average	139.9	118.2	28.1

[a]Control samples not immersed in Shelldyne H.

APPENDIX B

IMMERSION TEST RESULTS FOR NONMETALS

Table B.1. Immersion Test Results for Viton (US 3094).

Storage Temperature (°F)	Days in Test	Control Samples (Not Immersed)					Control Samples (Immersed)				
		Tensile Strength (psi x 10^{-3})	Strain (percent)	Volume Change (percent)	Weight Change (percent)	Shore A-2 Hardness	Tensile Strength (psi x 10^{-3})	Strain (percent)	Volume Change (percent)	Weight Change (percent)	Shore A-2 Hardness
70	43	1.30	746	-1	–	–	1.26	711	-4	-1.6	–
		1.29	732	-3	–	–	1.32	720	-8	-1.4	
	65	1.11	–	–	–	–	1.43	697	–	–	–
		1.58	800	–	–	–	1.53	800	–	–	–
	78	1.13	768	-1	-0.2	55	1.27	–	-5	-0.8	55
		1.12	691	-2	-0.2	55	1.49	772	0	-1.1	55
	105	0.82	653	0	-0.2	55	1.06	700	-5	-2.3	57
		1.00	753	-1	-0.2	55	1.24	–	-6	-2.2	57
	140	1.21	881	-1	-0.3	56	1.46	859	-4	-2.6	58
		1.23	828	-2	-0.3	56	1.40	737	-7	-2.5	59
	168	1.16	881	0	-0.3	53	1.58	713	-6	-2.4	56
		0.93	718	-1	-0.3	54	1.13	675	-7	-1.2	56
	Average	1.16	768	-1	-0.2	55	1.35	738	-5	-1.9	57
160	43	1.68	681	-3	-0.7	–	2.09	679	-8	-2.3	–
		1.55	618	-5	-0.4	–	2.11	648	-4	-2.3	–
	65	1.52	663	–	–	–	1.99	610	–	–	–
		1.63	756	–	–	–	1.89	597	–	–	–
	78	1.40	700	1	-0.1	58	1.91	656	-6	-1.8	59
		1.46	750	-4	-0.4	57	1.64	569	-2	-1.5	50
	105	1.39	673	-1	-1.1	57	1.37	600	-4	-1.4	59
		1.43	585	-5	-1.4	57	1.99	–	0	-1.3	59
	140	1.59	669	0	-1.6	57	1.70	644	-5	-2.0	58
		1.46	759	-2	-2.3	59	1.97	709	-3	-1.5	57
	168	1.41	737	1	-1.5	54	1.28	437	-4	-1.6	60
		1.52	737	0	-1.1	57	–	–	-9	-1.3	60
	Average	1.50	694	-2	-1.1	57	1.81	615	-4	-1.7	59

24988

Table B.2. Immersion Test Results for Viton/Nomex (US 941).

Storage Temperature (°F)	Days in Test	Control Samples (Not Immersed) Tensile Strength (psi x 10⁻³)	Strain (percent)	Volume Change (percent)	Weight Change (percent)	Shore A-2 Hardness	Control Samples (Immersed) Tensile Strength (psi x 10⁻³)	Strain (percent)	Volume Change (percent)	Weight Change (percent)	Shore A-2 Hardness
70	50	4.50	24	-2	0.3	–	4.97	26	0	1.3	–
		3.47	22	-2	0.3	–	5.86	22	-2	1.4	–
	72	3.77	27	–	–	–	4.33	40			
		4.11	30	–	–	–	5.27	30	–	–	–
	85	4.60	25	–	0.0	86	4.44	33	0	1.6	85
		3.60	23	-3	0.0	83	5.33	36	-2	1.7	87
	112	4.18	24	-5	0.3	84	4.43	35	0	1.3	86
		4.99	27	-9	0.5	83	4.00	31	-5	1.6	87
	147	5.13	29	-6	-0.1	83	5.53	31	1	1.8	86
		5.93	29	-6	-0.1	84	–	–	-3	2.1	87
	175	4.93	28	-3	-0.2	86	5.92	33	-4	1.2	87
		5.46	25	-6	-0.2	87	5.25	33	-3	1.4	[illegible]
	Average	4.56	26	-5	0.1	85	5.03	32	-2	1.5	86
160	50	4.67	21	-3	-1.4	–	4.68	25	-4	1.1	–
		5.70	–	-3	-0.6	–	5.33	25	0	1.2	–
	72	3.53	31	–	–	–	4.73	28	–	–	–
		3.60	35	–	–	–	5.60	32	–	–	–
	85	4.13	23	0	-1.1	83	5.27	33	-4	1.7	86
		5.27	27	-2	0.2	84	4.00	33	5	0.3	84
	112	5.10	34	0	-0.4	83	6.20	25	-4	1.2	87
		4.35	22	-2	-0.5	84	7.65	25	0	1.5	87
	147	4.86	24	0	0.0	85	6.80	27	0	0.9	85
		4.06	25	-3	-0.3	85	7.50	30	-3	0.9	85
	175	5.64	24	-2	-1.1	86	4.80	33	-1	1.2	87
		4.41	23	1	-0.2	–	5.27	32	0	1.2	86
	Average	4.63	26	-1	-0.5	83	5.65	29	-1	1.1	86

Table B.3. Immersion Test Results for N.trile (US 3010).

Storage Temperature (°F)	Days in Test	Control Samples (Not Immersed): Tensile Strength (psi x 10^{-3})	Strain (percent)	Volume Change (percent)	Weight Change (percent)	Shore A-2 Hardness	Control Samples (Immersed): Tensile Strength (psi x 10^{-3})	Strain (percent)	Volume Change (percent)	Weight Change (percent)	Shore A-2 Hardness
70	42	1.39	260	3	0.1	–	1.16	247	10	12.0	–
		1.41	296	9	0.1	–	1.32	286	8	12.0	–
	64	1.43	302	–	–	–	1.52	325	–	–	–
		1.49	303	–	–	–	1.35	320	–	–	–
	77	1.25	275	5	0.0	61	1.26	310	13	12.2	54
		1.36	290	7	0.0	61	1.19	285	9	12.2	53
	Average	1.39	298	5	0.1	61	1.30	296	10	12.1	54
160	42	1.46	243	-1	1.7	–	0.83	176	30	24.0	–
		1.53	237	-2	-1.9	–	0.99	194	27	24.2	–
	64	1.49	240	–	–	–	0.83	175	–	–	–
		1.56	235	–	–	–	0.61	155	–	–	–
	77	1.19	186	2	-0.8	64	0.84	170	30	20.8	57
		1.09	190	3	-1.2	62	0.89	199	27	20.9	55
	Average	1.39	222	1	-1.4	63	0.83	178	29	22.5	56

24992

24994

Table B.4. Immersion Test Results for Nitrile/Nylon (US 566 RL).

Storage Temperature (°F)	Days in Test	Control Samples (Not Immersed) Tensile Strength (psi x 10^{-3})	Strain (percent)	Volume Change (percent)	Weight Change (percent)	Shore A-2 Hardness	Control Samples (Immersed) Tensile Strength (psi x 10^{-3})	Strain (percent)	Volume Change (percent)	Weight Change (percent	Shore A-2 Hardness
70	42	7.50	53	0	0.0	—	7.55	28	0	10.0	—
		5.77	39	-1	0.1	—	7.36	29	-1	8.7	—
	64	7.40	34	—	—	—	7.64	49	—	—	—
		7.27	35	—	—	—	7.64	48	—	—	—
	77	7.46	48	0	-0.7	87	7.73	33	5	7.7	83
		7.91	48	-1	-0.8	86	7.64	48	-1	8.0	84
	104	7.35	40	0	-0.7	79	6.32	40	7	8.2	75
		7.63	45	0	-0.7	80	7.45	45	4	8.4	76
	139	8.00	58	10	-0.7	81	7.08	60	10	8.3	75
		7.00	40	5	-0.8	82	6.25	50	4	8.7	75
	167	6.45	30	3	-0.7	80	6.50	45	10	8.7	77
		6.25	32	8	-0.6	82	5.64	37	4	8.8	79
	Average	7.17	42	2	-0.6	82	7.07	43	4	8.6	78
160	42	6.79	44	-2	-1.7	—	8.32	44	3	13.1	—
		8.64	49	-4	-6.5	—	7.64	44	2	11.7	—
	64	8.09	50	—	—	—	8.18	50	—	—	—
		8.09	52	—	—	—	6.42	50	—	—	—
	77	7.80	44	0	-1.1	85	8.07	33	—	13.2	83
		7.73	43	-4	-0.4	90	8.00	48	4	12.0	83
	104	6.45	43	8	-0.9	82	7.17	—	26	13.2	77
		8.60	45	-4	-1.5	83	6.00	42	14	12.3	80
	139	6.55	47	-2	-1.7	82	7.17	51	21	13.8	77
		7.82	50	-4	-1.1	83	8.09	45	15	12.7	80
	167	6.15	32	3	-0.6	82	7.18	29	24	13.4	80
		6.55	43	0	-0.5	83	8.18	35	4	12.1	80
	Average	7.44	45	1	-1.6	84	7.54	43	13	12.8	80

Table B.5. Immersion Test Results for Ethylene Propylene Terpolymer (US 3015).

Storage Temperature (°F)	Days in Test	Control Samples (Not Immersed) Tensile Strength (psi x 10^{-3})	Control Samples (Not Immersed) Strain (percent)	Control Samples (Not Immersed) Volume Change (percent)	Control Samples (Not Immersed) Weight Change (percent)	Control Samples (Not Immersed) Shore A-2 Hardness	Control Samples (Immersed) Tensile Strength (psi x 10^{-3})	Control Samples (Immersed) Strain (percent)	Control Samples (Immersed) Volume Change (percent)	Control Samples (Immersed) Weight Change (percent)	Control Samples (Immersed) Shore A-2 Hardness
70	50	1.10	656	3	0.8	–	0.16	153	140	142	–
		1.14	653	-1	0.5	–	0.16	155	131	139	–
	85	0.96	633	-2	0.4	51	0.16	228	143	141	35
		0.96	578	-3	0.5	51	0.10	145	136	138	37
	Average	1.04	633	-1	0.6	51	0.15	170	138	140	36
160	50	1.24	648	12	0.6	–	0.04	108	220	222	–
		1.32	646	9	0.8	–	0.09	131	206	224	–
	85	1.13	490	14	-0.2	59	0.06	112	226	226	19
		0.91	490	16	0.1	52	0.04	150	216	219	19
	Average	1.15	569	13	0.3	56	0.06	125	217	223	19

24989

Table B.6. Immersion Test Results for Nylon.

Storage Temperature (°F)	Days in Test	Control Samples (Not Immersed) Tensile Strength (psi x 10^{-3})	Strain (percent)	Volume Change (percent)	Weight Change (percent)	Modulus (psi x 10^{-3})	Control Samples (Immersed) Tensile Strength (psi x 10^{-3})	Strain (percent)	Volume Change (percent)	Weight Change (percent)	Modulus (psi x 10^{-3})
70	57	6.80	54	-1	0.3	34.5	6.78	56	-9	1.6	35.4
		6.78	—	-7	-0.5	34.2	6.77	54	0	1.3	32.3
	82	7.69	93	—	—	39.0	6.99	88	—	—	44.4
		7.49	84	—	—	45.6	7.44	90	—	—	34.2
	98	6.19	71	0	-0.2	30.7	7.03	88	0	2.3	37.8
		6.91	83	-7	-0.2	36.4	7.04	100	1	1.3	40.0
	125	6.23	46	0	-0.3	21.0	6.38	87	0	1.0	35.0
		6.10	54	-4	-0.3	22.1	6.41	80	2	0.9	33.4
	160	7.53	60	0	-0.4	31.5	—	—	-1	1.3	—
		7.26	70	-5	-0.5	29.8	7.22	63	1	1.2	30.9
	188	7.16	60	0	-0.7	36.5	7.05	72	-2	1.3	21.0
		7.60	60	-8	-0.7	31.9	6.44	85	-2	1.4	21.0
	Average	7.15	67	-3	0.4	32.8	6.87	78	-1	1.4	33.2
160	57	9.84	48	-7	-2.4	49.8	8.20	54	4	0.3	39.2
		9.95	56	2	-2.2	52.2	8.20	54	-1	-0.2	39.8
	82	11.01	55		—	45.6	9.23	70	—	—	33.1
		10.88	50	—	—	61.0	8.79	78	—	—	37.5
	98	11.51	53	1	-2.9	58.4	9.03	55	1	0.5	41.7
		11.53	4[illegible]	-5	-2.7	59.5	9.35	65	-1	-0.2	37.2
	125			-1	-2.7	40.5	8.30	50	1	-0.4	23.2
		10.50	3[illegible]	2	-2.6	39.4	8.60	50	-1	-0.5	45.7
	150	10.65	36	1	-3.0	37.7	8.68	45	-1	-0.3	40.0
		10.51	42	-2	-2.8	37.5	7.53	22	-1	-0.5	40.0
	188		20	-1	-3.1	36.4	9.20	43	2	0.5	27.2
		10.23	25	-2	-2.9	48.2	9.61	48	-3	0.3	43.6
	Average	10.66	42	2	-2.7	47.2	8.73	53	0	-0.1	37.4

24991

Table B.7. Immersion Test Results for Teflon.

Storage Temperature (°F)	Days in Test	Control Samples (Not Immersed) Tensile Strength (psi x 10⁻³)	Strain (percent)	Volume Change (percent)	Weight Change (percent)	Modulus (psi x 10⁻³)	Control Samples (Immersed) Tensile Strength (psi x 10⁻³)	Strain (percent)	Volume Change (percent)	Weight Change (percent)	Modulus (psi x 10⁻³)
70	58	2.72	413	0	0.0	—	1.84	211	1	0.5	16.0
		2.96	419	0	0.0	20.7	2.93	407	0	0.2	16.0
	83	3.29	357	—	—	17.5	2.53	222	—	—	17.5
		3.00	305	—	—	17.5	2.84	295	—	—	17.7
	99	2.74	454	0	0.1	13.3	—	—	0	0.8	13.8
		2.55	390	0	0.1	13.[illegible]	2.71	396	7	0.2	13.4
	126	3.03	425	0	0.0	14.3	2.03	255	2	1.5	14.4
		2.95	397	-2	0.0	14.8	2.50	407	4	0.6	18.2
	161	2.61	460	3	0.1	12.5	2.37	395	-2	1.1	11.3
		2.94	415	5	0.0	13.3	1.67	273	4	0.4	12.0
	189	2.28	376	0	0.0	14.7	2.22	348	-2	1.2	13.8
		2.16	346	3	0.0	16.1	2.28	353	0	0.4	12.9
	Average	2.77	398	1	0.0	15.3	2.36	324	1	0.7	14.8
180	58	2.01	253	1	0.0	17.4	2.69	370	1	0.5	17.4
				0	0.0	—	2.82	396	1	0.2	17.8
	83	2.19	177	—	—	18.1	2.66	272	—	—	16.5
		2.24	190	—	—	18.3	3.19	344	—	—	17.7
	99	1.77	212	1	0.1	13.9	2.83	403	—	0.3	13.1
		1.84	193	1	0.1	13.7	2.36	310	0	0.4	13.5
	126	2.00	360	-1	0.1	14.2	2.56	373	1	0.4	14.2
		1.76	257	-2	0.1	14.2	2.64	360	1	0.5	14.2
	161	2.79	466	-1	0.0	14.4	2.13	293	1	0.4	14.2
		2.77	457	-2	0.0	14.2	2.68	406	1	0.5	12.2
	189	1.81	300	-1	0.0	12.6	2.13	337	1	0.5	12.3
		1.58	250	-2	0.0	13.9	2.29	360	0	0.5	14.6
	Average	2.07	265	-1	0.0	15.0	2.58	354	1	0.4	14.8

24998

Table B.8. Immersion Test Results for Silicone Rubber.

Storage Temperature (°F)	Days in Test	Control Samples (Not Immersed) Tensile Strength (psi x 10⁻³)	Control Samples (Not Immersed) Strain (percent)	Control Samples (Not Immersed) Volume Change (percent)	Control Samples (Not Immersed) Weight Change (percent)	Control Samples (Not Immersed) Shore A-2 Hardness	Control Samples (Immersed) Tensile Strength (psi x 10⁻³)	Control Samples (Immersed) Strain (percent)	Control Samples (Immersed) Volume Change (percent)	Control Samples (Immersed) Weight Change (percent)	Control Samples (Immersed) Shore A-2 Hardness
70	58	0.84	378	-5	0.7	–	0.56	183	16	15.9	–
		0.89	310	1	0.6	–	0.56	191	13	16.0	–
	83	0.79	330	–	–	–	0.51	240	–	–	–
		0.86	357	–	–	–	0.56	250	–	–	–
	99	0.92	302	-4	0.4	–	0.35	196	22	16.4	–
		0.44	194	1	0.3	–	0.45	235	19	15.9	–
	189	0.51	203	-5	0.5	52	0.36	157	19	16.3	47
		0.60	230	-1	0.4	52	0.32	230	19	16.3	47
	Average	0.72	288	-2	0.5	52	0.46	210	18	16.1	47
160	58	0.86	310	2	0.3	–	0.69	230	27	23.8	–
		0.83	280	-2	-0.1	–	0.73	265	38	23.7	–
	83	0.86	320	–	–	–	0.51	240	–	–	–
		0.87	320	–	–	–	0.54	260	–	–	–
	99	0.89	297	2	0.1	–	0.52	292	27	21.1	–
		0.75	278	-2	0.1	–	0.55	275	38	21.4	–
	189	0.40	200	1	-0.6	54	0.32	183	21	22.6	47
		0.39	195	-2	-0.2	52	0.45	200	26	22.6	45
	Average	0.73	275	0	-0.1	53	0.54	243	30	22.5	46

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13. ABSTRACT

A 7-month compatibility effort was conducted on materials potentially useful in ramjet fuel systems using the dense hydrocarbon fuel RJ-5 (Shelldyne H). The results of this work were used to select materials for a full-scale fuel system simulator to be tested in the remainder of this program.

The candidate materials included eight metals and eight nonmetallic materials. Immersion tests were conducted on all materials at both room temperature and at 160° F, with the specimens evaluated by changes in appearance, volume, weight, tensile properties, and hardness.

Additional compatibility tests were conducted under a high shear environment typical of ramjet turbopumps and under vibrational and flexing loads typical of aircraft carriage and missile flight. For these tests, the materials were kept in contact with hot Shelldyne H.

Candidate bladder materials were subjected to hot pressurant gases from solid-propellant gas generators, while in contact with fuel in a simulated fuel cell. Low temperature mechanical properties were determined for these elastomers.

None of the eight metals (two steels, two stainless steels, two aluminums, and two titanium - have shown any effect of contact with Shelldyne H. The fuel tank material selected was 4130 steel, from considerations of compatibility, ease of fabrication, and cost. Steels, stainless steels, and aluminums were selected for other components of the simulator.

The bladder material chosen was a Viton/Nomex composite, from considerations of fuel compatibility and hot pressurizing gas compatibility. It is expected that this material will be suitable for low temperature operation, but alternate materials and composites may be tested in the simulator. Viton was selected as the primary seal and O-ring material, with nitrile also to be tested. Nylon and Teflon, both compatible with Shelldyne H, will be used, where applicable, for components of the simulator.

Nitrile and silicone rubbers were shown to absorb a significant amount of fuel, swell, and lose tensile strength as a result of immersion. A nitrile/nylon composite material did absorb fuel and swell, but its tensile properties were not degraded. Ethylene propylene terpolymer was incompatible with Shelldyne H.

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